# Development and application of dynamic models for environmental management of aquaculture in South East Asia.

A thesis submitted to the University of Stirling

for the degree of Doctor of Philosophy

by

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**DECLARATION**

I declare that this thesis has been composed by myself and that it embodies the results of my own research and all work contained has not been submitted for any other degree. All research material has been duly acknowledged and cited.

Signature of Candidate

_______________________________________

Lynn Irene Munro

Date: 31st March 2014

# ABSTRACT

With the world's population set to reach 9 billion by the mid 21st century food security has never been more important. Increased competition regarding land for agricultural use and over fished seas means it falls to aquaculture to meet the global demands for protein requirements. The largest supply of aquaculture products are cultivated in South East Asia where the industry has seen rapid expansion, particularly of pond production in the past 50 years. This initial expansion has come at a cost with mangrove losses and eutrophication of natural water sources resulting. The impact of these not only affects other stakeholders, including domestic users, but effects will be felt by the aquaculture industry. Indiscriminate release of effluents to the surrounding water reduces the water quality for other users and may impact on the farm discharging the water originally. Poor water quality can then result in poor growth rates and increased mortalities reducing the profitability of the farm and endangering the livelihood of the farmer.  If aquaculture is to meet the global food demand it is important that current and future enterprises are developed with sustainability at the fore front.

This study investigates the nutrient dynamics in pond culture in South East Asia, focussing initially on four countries outlined by the SEAT (Sustainable Ethical Aquaculture Trade) project, including Thailand, Vietnam, China and Bangladesh. Within the four countries the main species cultured for export were identified resulting in tilapia, shrimp, pangasiid catfish and prawn. Following a farmer survey designed to collect a large volume of data over a range of topics

including, water management, social, economic and ethical perceptions, dynamic models were developed, using Powersim Studio 8© (Powersim, Norway), for a generic fish and shrimp ponds separately. The models draw on data from the survey combined with other literature sources to provide outputs for Total Nitrogen and Total Phosphorus in water and sediment as well as dissolved oxygen in the pond water.

One of the biggest challenges facing this study was the objective selection of relevant sites for case studies to apply the models to. With such a large preselected set of sites (200 per species per country) it was important that the method be capable of handling such large datasets. Thusly it was decided that a multivariate method be used due to the removal of any pre judgement of the data relevant to the study. In order to investigate the nutrient dynamics water management data was used in the multivariate analysis to identify any similarity between the practices occurring on farms.

The case studies in this project focus on Thailand and Vietnam, covering tilapia, shrimp and pangasius. Prawn farms were disregarded as, through the survey, it was discovered most production was for domestic trade. The models were adapted to each farm case study expanding the boundary from pond level to farm level, providing an output for each pond in terms of nutrients in the water and production levels and the farm as a whole for dissolved oxygen and sediment accumulation. The results of the models suggest the culture species to be taking up much of the TN added followed by the accumulation in sediments in shrimp ponds, while TP is mostly taken up by sediments. The fish case studies suggest that most of the TN is discharged to the environment followed by uptake. While Total phosphorus shows similar results to shrimp, accumulating in the sediment. The models presented in this study can be used to estimate outputs from farms of similar water management strategies and can assist in the determination of where improvements can be made to reduce the potential for eutrophication of natural water sources.

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# CHAPTER 1

# INTRODUCTION

The past three decades have seen a marked elevation in aquaculture production, owing to an increase in global population food demand, and the requirement for improved food security being at an all time high (De Silva & Davey, 2009). Due to many influences and vulnerabilities of aquaculture practices through external pressures, such as competition from other water users, environmental degradation and disease outbreak, some countries have slowed or ceased the expansion of inland aquaculture (Bostock et al, 2010). However this is not the case in SE Asia, which has seen massive expansion in just the last 6 years (FAO, 2012). SE Asia is the largest contributor to global aquaculture, producing over 80% of all products, shown in fig 1.1 (Lymer et al, 2008; FAO, 2012). China has emerged as the largest national producer (Table .1.1), which when combined with the other major producing countries, Indonesia, Thailand, India, Vietnam and Bangladesh, makes up approximately 89% of total global aquaculture, by volume (Gordon and Kassmam, 2011). This ever expanding industry has now resulted in aquaculture production accounting for nearly half of global fish production and is still increasing; looking set to overtake fisheries production by 2020, if current increasing trends continue, as world stocks are reportedly declining (FAO, 2012). Although much of the increased production was originally to improve national food security, governments of each country have recognised the benefits of producing and exporting to global markets and thus the ever greater intensification of farming techniques has emerged (Hishamunda et al, 2009a). In order to maintain environmental, social and economic stability, it is important for these ventures to take a sustainable approach to their development (Collis, 2012; Dey *et al*., 2005).

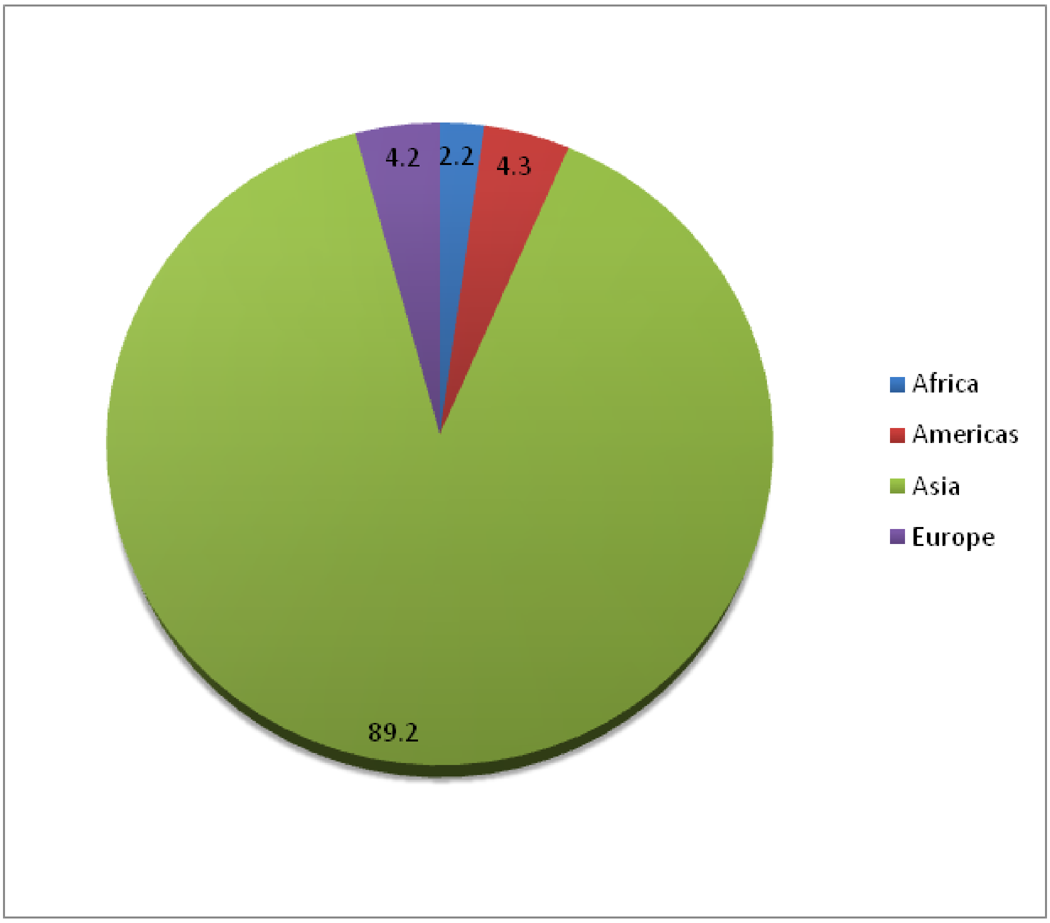



Figure 1.1 Chart indicating percentage world aquaculture production by region (after FAO, 2012)

**Table 1.1: Aquaculture production in SE Asia by country (after FAO, 2012)**

| Top six aquaculture producing countries in SE Asia | Total Aquaculture Production (Tonnes) |
|---|---|
| China | 36734215 |
| India | 4648851 |
| Viet Nam | 2671800 |
| Indonesia | 2304828 |
| Bangladesh | 1308515 |
| Thailand | 1286122 |

## Aquaculture in South East Asia

The practice of aquaculture in South East Asia is not a new concept; it has been around for thousands of years according to literature, with archaeological evidence pointing towards it originating in China (Hishamunda *et al,* 2009a; Costa-Pierce, 2002; Nash, 2011). However over the past 50 years there has been a massive expansion and changes in the methods of cultivation, resulting in increased pressure on the surrounding ecosystems (Sapkota *et al*., 2008; Naylor *et al*., 2000). Major rivers used as a source of water for aquaculture are still used by local communities for domestic purposes including cooking, cleaning and washing. Eutrophication events in water sources can result in potential harm to human health as well as causing major issues on aquaculture farms, increasing mortality rates (Boyd, 1998). With increasing urbanisation around water sources in SE Asia it is important for all water users to behave in a responsible manner with regards to water use, treatment and discharge (Collis, 2012).

There are several types of production system used in SE Asia by farmers with pond culture and cage culture at the forefront. *Oreochromis niloticus* or Nile tilapia, a major fish culture species, has traditionally been grown in earthen ponds (Molinar et al, 1999). Pond culture has some advantages over cage culture including increased biosecurity and potentially lessening the direct impact on the environment (Rana et al, 2009). This has culminated in a move from cage culture to pond culture in many Asian countries (Anh et al, 2010). Up until 2004 Vietnamese farmers preferred to grow *Pangasius bocourti* in cages in the main body of the river, under suspended houses or floating huts, however in recent years there has been a mass shift from this type of production to pond culture using *Pangasianodon hypophthalmus* (Phuong & Oanh, 2010, Cuyvers & Van Binh, 2008). The shift from cage culture to pond culture has resulted in higher initial financial outlay due to the price of land combined with the cost of constructing excavated ponds, however higher production volumes have been reported from ponds not significantly larger than their cage counterparts, thus increasing profits. (Cuyvers & Van Van Binh, 2008).

Shrimp farming in SE Asia has a controversial history. It was originally thought that the majority of mangrove destruction in Asia was due to the expansion of shrimp culture around coastal regions (Naylor et al, 2000). It is understood that mangroves have always been exploited by humans, however with increasing urbanisation and the increasing demand for food, clearing the forests for aquaculture has resulted in an increased global decline in mangrove coverage

(Seto and Fragkias., 2007; Flaherty and Karnjanakesorn, 1995). The data available on mangrove clearance is sparse and not entirely reliable, which has resulted in more focus on archiving and utilising historical satellite imagery. Alongi (2002) asserted, through the compilation of various studies, that the greatest reduction occurred in Thailand, Vietnam, Mexico, Singapore and the Phillipines (Table 1.2). In Singapore the loss appears to have occurred over a 100 year period due to increased urbanisation (Spalding *et al*., 1997). The others are the result of expanding pond aquaculture and have been incurred over a period of approximately 30 years at a rate of between 1 and 20% per year (Alongi, 2002).

In Thailand there is some evidence to support this due to government encouragement of mass expansion of the shrimp farming industry with little regard for the effect on the environment (Hishamunda et al, 2009b). Expansion coupled with intensification of practices resulted in many waterways becoming more polluted and increases in flooding events due to mangrove removal. This has been recognised by the Thai government who have now produced new regulations requiring impact assessments to prevent further destruction of mangroves; so halting coastal erosion, which could cause major environmental and economic disaster.

**Table 1.2: Estimater percentage loss of mangroves over a specific time period for countries deemed to have major losses (Seto and Fragkias, 2007; Alongi, 2002; Spalding et al., 1997)**

| Country | Approximate mangrove loss | Time period |
|---|---|---|
| Thailand | 50% | 1975-1991 |
| Vietnam | 25% | 1980-2000 |
| Mexico | 65% | 1970-1997 |
| Phillipines | 60-75% | 1952-1997 |

## Environmental concerns of Asian aquaculture

Aquaculture utilises natural resources and has previously been associated with environmental degradation (Pillay, 2004; Beveridge et al, 1997). The degradation of surrounding water quality has been attributed to the intensification of many aquaculture practices regardless the of the production system (Black, 2000) and specifically in South East Asia intensification of aquaculture has assumed responsibility for much of the mangrove destruction around coastal regions (Dierberg and Kiattisimkul, 1996; Naylor et al, 2000). As previously mentioned aquaculture practices have moved away from cage production systems and into pond culture through the belief that a closed system would result in more control over the quality of the water in the farm and in discharge, possibly reducing direct environmental effects and increasing production (Beveridge et al 1997; Rana et al, 2009). As previously mentioned the removal of mangroves has contributed to coastal erosion resulting in increased occurrences of flooding events in some regions (Paez- Osuna, 2001b; Mazda et al, 2002). However another major concern is the indiscriminate release of farm effluents due to the reliance on water bodies by local stakeholders for domestic purposes (Martinez-Porchas and Martinez-Cordova, 2012). This is compounded by the removal of mangroves, which are highly productive environments able to assimilate much of the waste products discharged from aquaculture ponds (Pillay, 2004). The move to ponds may have resulted in more control for the farmer over water quality, however due to a shift from extensive aquaculture to intensive, combined with large amounts of water exchange there is the possibility that if an aquaculture system is poorly managed the chance of eutrophication increases resulting in potential degradation of surrounding water bodies due to increase loading of nutrients (Pillay, 2004). As it is well documented that aquaculture farms tend to use the same water body as both their source and effluent receiver (SEAT, Unpublished data, 2013) it is important for farmers to minimise their impact on the environment especially as many areas near aquaculture systems are becoming more urbanised adding extra pressure on water bodies (FAO, 2012). It is therefore in the best interest for aquatic farmers to maintain good quality standards as self pollution may result in major losses of stock and thus profit reduction.

## Environmental regulations for aquaculture in SE Asia

Environmental regulations are the driving forces for managing aquaculture activities in many countries. In order to increase national income and improve food security, the expansion of aquaculture in SE Asia saw a massive growth, outstripping that of capture fisheries (FAO, 2010). In the early expansion period many governments allowed farm construction in most regions without assessing the impact on the surrounding environment (Hishamunda, 2009b). It is well documented that pond aquaculture in SE Asia is prone to indiscriminate discharge of effluents to water bodies, which has, in the past, resulted in eutrophication events, loss of biodiversity and farm production losses (Naylor et al., 2000). As previously mentioned, mangrove clearing played a prominent role in the expansion of aquaculture, particularly in Vietnam and Thailand (Spalding *et al*., 1997). This resulted in increased levels of turbidity in natural water ways, the release of some toxic wastes and an overall reduced water quality due to the reduced productivity (Algoni, 2002). This combination of factors resulted in polluted waterways, making domestic use harmful and may have resulted in the short life span of farms, in particular shrimp (Paez-Osuna, 2001a). Many governments have recognised the need to introduce policies to counteract the effect of unregulated expansion. Vietnam, Thailand and the Philippines introduced a complete ban on the further development of mangroves though have allowed current farms to continue their practices. In Indonesia lessons have been learned early resulting in the complete ban on any development on the Island of Java with any other development requiring both 100m of mangrove to be left between the development and the ocean and the requirement of an Environmental Impact assessment (EIA) (Hishamunda *et al*., 2009b). Although the Indonesian government has introduced the requirement of and EIA, this is still not standard practice in other countries. Neither Thailand nor Vietnam currently requires the submission of an EIA for aquaculture development, however the Thai government is moving towards a strict policy involving permit applications which legally require the inclusion of an EIA (FAO, 2013). Although there have been strides towards developing environmental regulation to improve sustainability, there is still a long way to go in enforcement as there have been some reporting that mangrove clearing still occurs in the Mekong Delta, Vietnam (Hishamunda et al., 2009)

## Modelling aquaculture water quality

It is becoming more prominent that groups interested in environmental management of any kind are turning to predictive numerical models to provide answers to complex environmental questions while reducing the need for collection of large data sets (Ford, 2010), and allow pro-active management of aquaculture rather than retrospective mitigation. Many environmental regulators currently have models in place to investigate aquaculture impacts. These are often specific to the practices prevalent in each country and require detailed calibration for local parameters such as wave action and current speed for open water models and source water quality and effluent discharge for inland models (SEPA, 2010; US EPA, 2010). Although environmental modelling work has been carried out, for aquaculture globally by Nobre et al. (2010); Jiminez-Montealegre et al. (2002) and others.

Nobre (2010) produced a model for nutrient loading on a bay in China from large aquaculture production and catchment usage, using a multilayer ecosystem model. The model encapsulates a variety of modelling applications including aquaculture system models, organic matter and water transport models and spatial modelling. The outcomes of the model provide indications for not only the nutrient loading but can address whether the changing of location of shellfish farms would benefit both production levels and the estuary. While this study focuses on coastal aquaculture production, pond culture has come under major focus for modelling efforts. There are various models which have been developed for pond aquaculture, many focusing on nutrient balances for particular ponds. Jiminez-Montealegre *et al*. (2002) developed a model for nitrogen transformation and flux for application in tilapia and tambaqui ponds. Although the model only covers three components; fish, phytoplankton and the sediment-water interface, it is complex in its construction and, as stated by the author, requires a high level of data input reducing its range of applicability. Many models consider water quality with particular focus on a single aspect. Buford and Lorenzen (2004) produced a nitrogen dynamics model for shrimp ponds with particular focus on sediment remineralisation. The model requires less data input to run and has been calibrated and validated using a large set of time series data thus resulting in comparable results with other studies (Briggs and Funge-Smith, 1998; Jackson *et al*., 2003)

Other models cover system combinations such as IAAS (Integrated Aquaculture/Agriculture Systems). These systems are popular but have had little attention until Jamu and Piedrahita (2002a) developed a model to assess the transport of nutrient between the two systems. The model uses a short timestep of 0.125 days to increase the accuracy of the interactions between the various submodels and was based on a fertilised tilapia pond for a site in

Rwanda. The model has been shown to perform well for nitrogen and organic matter transport, however required refining for phytoplankton production.

As it is clear that environmental degradation is major concern where aquaculture production is concerned it is imperative that water management practices are scrutinised in order to move towards increased ethical and sustainable aquaculture practices that will help to achieve global food security.

## The SEAT project

The SEAT (Sustainable Ethical Aquaculture Trade) project was an EU FP7 funded project from 2009 to 2013, investigating the sustainability of aquaculture product trade between SE Asia and the EU looking specifically at four major aquaculture products; tilapia, pangasiid catfish, penaeid shrimp and *Macrobrachium* prawn. The project investigated a wide variety of scientific and social science research topics, including environmental quality of the production systems, as this was found to be a major concern during the scoping studies of the project (Murray et al, 2011)

The current public image of SE Asian aquaculture is often poor worldwide due to misunderstandings of the practices associated with the culture of the species under investigation (SEAT, 2013). It is therefore essential that environmental sustainability of aquaculture at farm and local level is improved in order to maintain or enhance future trade and improve food security both within producer counties and globally.

## Aims and objectives of the research

The aims of the research described in this thesis are to:

- Develop pond level, dynamic models for fish and shrimp ponds, investigating the nutrient and dissolved oxygen dynamics
- Characterise groups of farms for each species in each country using multivariate methods to determine any similarity, thus objectively selecting a subset of sites from a much larger preset group.
- Further develop the initial models from pond level to farm level and apply them to individual case study farms for tilapia, shrimp and pangasiid catfish in Thailand and Vietnam in order to determine nutrient dynamics and accumulation in aquaculture farms.

With the increased importance of food security, the aquaculture industry can fulfil the requirement for food production globally. Much of the aquaculture industry is located in SE Asia, which has undergone massive expansion over the last 50 years. Increased production has come at a great cost to the environment, though there are now efforts to improve and regulate the discharge of pollutants from farming systems. In order for aquaculture to grow in a sustainable manner it is important to monitor the water quality being discharged into the surrounding environment in order to avoid eutrophication events in natural water bodies.

This study intends to investigate the role of water management practices on the levels of total nitrogen (TN), total phosphorus (TP) and dissolved Oxygen (DO) levels in the culture system water and the sediment. Further it will demonstrate the key sinks of nutrient accumulation in each system investigated.

This study takes a practical approach to modelling. Chapter 2 provides the general methodology on the selection of the relevant sites for the SEAT project as a whole with some generalised outcomes for each country. It will go on to briefly introduce the idea of refined site selection within the boundary of the SEAT outcomes and the collection and analysis of data used for the models. The 3rd chapter outlines the modelling methods and the development of dynamic models with boundaries defined for shrimp and fish ponds using literature data. The thesis will then go on to investigate the challenges of site selection in a large integrated project in chapter 4, and how through the use of multivariate analysis can be both objective and cohesive with the larger scale. Chapter 5 and 6 then leads on to the model case studies split by country. The case studies focus on Thailand and Vietnam, using farm sites selected in chapter 4 as representatives of the group they belong to. Outputs for levels of TN and TP in the water and sediment are provided as well as the level of DO in the pond water throughout the cycle. The thesis will conclude with a general discussion touching on the importance of modelling in environmental regulation and general water quality in relation to pond aquaculture.

# CHAPTER 2

# SITE SELECTION AND SAMPLE COLLECTION

## 2.1 Initial site selection for study sites

The sites used for this study were derived from those used for the EU 7FP SEAT project. The initial site selection was based on desk studies to determine the best countries to take forward in the action plan. This resulted in the project focusing on four countries; Thailand, Vietnam, China and Bangladesh as these are among the major aquaculture producing countries (FAO, 2011). Following this, four main species were chosen for the project tilapia, shrimp, pangasiid catfish and prawn, focusing on the 2 main species for export in each country. The overall sites for SEAT were derived from local government and official sources where clusters of farms were identified for further study (Murray *et al*., 2011). These sites were then contacted in order to determine their participation for a survey to be conducted on their aquaculture site involving questions based on farm management, financial and social issues.

## 2.2 Farmer Survey

The farmer survey was designed as a tool for gathering essential information on farming activities. The survey was compiled by work packages (WP) 2-8 and covered the topics outlined in table 2.1. Through a scoping study conducted earlier in the project by WP2, 400 farms were selected for the application of the survey; 200 for each species in the country under investigation. Each work package submitted a series of questions, which were then compiled into the large questionnaire. This was then trialled over a month in each country in order to refine the questions by either rewording specific questions or removing duplicates that were found.

The data required for the model parameterisation and verification (WP4) were identified and a survey was developed for the “Water management” practices at each farm as this was determined the best way to gather a large volume of information about individual farms over a wide ranging area. These included questions regarding water sources and treatment, water exchange rates, sediment removal (see appendix 1). Questions regarding cage sizes, feed additions and river flow rates, for open systems were submitted, however during further discussions with other work packages, open systems were disregarded and therefore the questions relating to open systems were removed from the final survey.

It was discovered that some farmers were uncomfortable providing information regarding water management practices due to previous negative media attention on aquaculture in SE Asia, which had driven down the sell price of their products. This indicates the impact of global perceptions on the aquaculture industry.

## 2.3 Site Selection

The original site selection carried out by the SEAT project contained a bias based on location of clusters. In order to mitigate the bias for the study, a multivariate analysis was carried out. The use of multivariate analysis allowed the sites to be focused more on the water management practices on the farm than simply the location and therefore increased relevance to the study undertaken. A cluster analysis was carried out on the results from the water management section of the survey, having converted the data into a binary format. Using the Jaccard coefficient, dendograms showing the relationship each activity has to the other were produced. This provided clusters of farms based solely on water management practices observed and therefore providing a sample set relevant to the outputs of the models constructed. Sites from each group were then randomly selected as case studies for application to the model and required further data collection. The full methodology is outlined in the next chapter of this study.

## 2.4 Data Collection

In order to verify the models for each case study, data from the selected farms was required (see Chapter 3 for selected study farms and selection methods). Thai tilapia and shrimp farms had samples collected on four occasions during the year due to their continuous culture period, whereas the Vietnamese farms had samples collected on two occasions during the year (rainy and dry season) as they only have a single culture period per year. The sampling occasions are outlined in Table 2.2 for each country. Table 2.3 outlines the sample type and parameters collected at each farm. Water samples were collected in new, 500 ml polyethylene containers and transported to laboratories using cool boxes to prevent the degradation of the samples. Sediments in Vietnam were collected using sediment corers with a 9cm diameter and kept in airtight containers until ready for drying. Thai samples were collected using an Ekman grab sampler with a 36cm surface area, which were oven dried at $60^{o}C$ for 24 hours, while

Vietnamese samples were air dried for 7 days. Vietnamese samples were analysed in the fisheries department of Can Tho University whereas the Thai sediment samples were shipped to the University of Stirling to be analysed. The feed samples were similarly collected and placed in sealed containers to await drying for further analysis. Analysis of water samples was carried out in each country. Analysis of sediment and feed samples were carried out in Vietnam, or transported as dried sample to Stirling, UK, for analysis (Thailand).

**Table 2.1: Sampling occasion points for each case study country**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Au | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thailand | | | | | | | | | | | | |
| Vietnam | | | | | | | | | | | | |

**Table 2.2: Parameters analysed from aquaculture farms**

| Water quality data | Sediment | Feed |
|---|---|---|
| TN (mg/l) | TN (ug/g) | TN (%) |
| TP( mg/l) | TP (ug/g) | TP (%) |
| Temperature ($^oC$) | | |
| DO (mg/l) | | |

## 2.5 Sample analysis

In Vietnam, water samples for TN and TP were refrigerated until ready for analysis. Once ready the samples were prefiltered and analysed using the Macro-Kjeldahl method and Stannous Chloride method for TN and TP respectively, according to Bartram and Balance (1996). Both methods have acceptable detection levels for the analysis. The Macro- Kjeldahl method detection range is 0-100mg/l and the Stannous Chloride method will detect 3 ug P /l. Sediment and feed samples were also analysed using the above methods by adjusting the loading to 0.2g of feed and 2.0g of sediment. The water samples in Thailand were analysed in Kasetsart University also using the Kjeldahl method for TN, while the TP was analysed using the Ascorbic acid method, according to the APHA standard methods (2005), with a minimum detectable level of 10 ug P/l.

Dried sediment and feed samples received at Stirling University from Thailand were analysed for total nitrogen and total phosphorus. Total nitrogen was analysed by Perkin Elmer 24000 CNH/SO autoanalyser, using 3 sub-samples to provide a consistent percentage by dry weight content for each sample. Total Phosphorus was analysed using a Nitric acid digestion method. Again using three sub-samples per sample. Digestion was achieved using 5ml of 69% Nitric Acid in a microwave digester at 190$^{o}$C for 20 mins. The digests were diluted by a factor of 24 to reduce the absorbency of the sample in order to produce a measurable result. They were then analysed by inductively coupled plasma – mass spectrometry using a Thermo X Series 2 ICP MS with a CCT correction to provide the output in mg/g of sample for TP. ICP MS analysis has a detection limit of 1ug P/l for a 0.05 g sample making this the most sensitive of the 3 methods for sediment analysis by a factor of 10.

Colorimetric methods are still used widely in phosphorus detection in samples, however the ICP MS provides a preferable alternative to the classic methods as it has a much shorter analysis time (12 minutes per sample) and has an even lower detection limit than the Stannous Chloride and Ascorbic Acid method.

The TN levels detected in sediments for this study were analysed using 2 different methods, The Kjeldahl method and through the use of an auto analyser. The Kjeldahl method provides an output of mg/g whereas the CN analyser results in a percentage TN content in the sample. The Kjeldahl method may be preferable where a mass value is required, however for the models developed in this study a percentage content of TN and TP was used for the feed and sediment.

## 2.6 Powersim Studio 8

Powersim Studio 8 is a modelling program based on object oriented conceptualisation. The software allows the user to visualise the system as it is modelled by inserting equations and parameters into objects such as constants, auxiliaries, flows and levels. This method provides the opportunity for modelling without the demand for in depth knowledge of differential calculus though differential equations are easily modelled. It is important to understand that Powersim is not a multi platform program. It requires a personal computer using a Microsoft Windows© operating system.  Powersim Studio 8 requires at least Windows XP and is compatible with the latest release of the operating system (Windows 8)

The program provides options for time measurement, offering both calendar dependent and calendar independent simulations. Preset time units and series resolutions can be selected based on a calendar dependant simulation, whereas these must be defined by the user for non-calendar dependant simulations. First order equations are solved using the Euler order preset in the program, this however can be changed, if required, to Runge-Kutta. As previously mentioned equations are constructed using specific objects. Levels show material accumulation and are indicated by a rectangular box. Flows transport data both into and out of the level and are always time dependant. For example births and deaths in a deer population (individuals/month) (Ford, 2010). Constants contain the factors which affect the system to be simulated and are represented by a diamond shape in the model diagram. The final component is the auxiliary, shown as a circle. This object contains equations formed from constants and other auxiliaries to provide information to flows. These objects are connected together using a link, represented by an arrow showing the direction the information is travelling (table. 2.3)

Karlsson and Persson (1998) provided a list of the working procedure that takes place during a simulation initiated in Powersim (table 2.4). It shows how initial calculations are conducted, followed by the application of the time step, which then runs the calculations according to the time step applied.

**Table 2.3: Objects available in Powersim Studio 8 for compilation of a model and a short description of their application within the model**

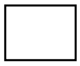
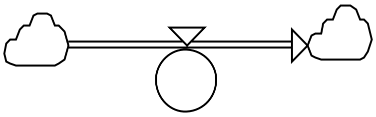
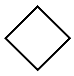
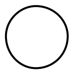
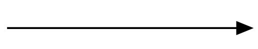
| Powersim Object | Application |
| --- | --- |
|  Level | Material accumulator |
|  Flow | Information transport into or out of Level |
|  Constant | Input information to model |
|  Auxilliary | Equation source |
|  | Link: Indicates the directional flow of information |

**Table 2.4: Table taken from Karlsson and Persson (1998) showing the actions taking place during a Powersim simulation**

| Step in simulation | Action |
|---|---|
| 1 | TIME =0 |
| 2 | Levels are initiated |
| 3 | Auxiliaries are calculated |
| 4 | Flows are calculated |
| 5 | TIME=TIME+TIMESTEP |
| 6 | Levels are calculated |
| 7 | Auxilliaries are calculated |
| 8 | Flows are calculated |

# CHAPTER 3

# DEVELOPMENT OF POND AQUACULTURE MODELS FOR GENERIC FISH AND SHRIMP

## 3.1. Introduction

Environmental models are increasingly popular with environmental regulation bodies as they allow the gathering of information about a system without the need for exhaustive data collection which costs both time and money (Ford, 2010). There are currently a variety of models in use throughout the world which are tailored to specific systems for various purposes. Popular models include DEPOMOD and WASP used by the Scottish Environment Protection Agency and the United States Environment Protection Agency, respectively, providing  simulations of the dispersion of waste from cage farming systems, while WASP investigates the transport and fate of nutrients and other contaminants in surface waters (Cromey *et al.*, 2002; SEPA, 2013; EPA, 2013). While these models have been widely used by environmental regulators other models are constantly under development for research purposes. When using such tools it is important to have an understanding of the system being modelled in order to develop simulations which accurately reflect the processes that occurs (Ford, 2010). There have been a number of studies into the effects of aquaculture on the environment. Jamu *et al.* (2002a) considered the integration of aquaculture with agriculture, showing how the effect of deteriorated water quality in pond systems can have a major effect on agricultural systems if not managed properly. Jackson *et al.* (2003) regarded impacts of the deposition and remineralisation process in shrimp ponds. Many studies focus on the fate of contaminants within a culture system and apply approximations for volumes of feed and fertilisers added, though few consider the variation in production practices which can occur within single species culture.

## 3.2. Pond aquaculture farming practices

Aquaculture production is increasing drastically in SE Asia at a rate quicker than that of marine capture fisheries and agriculture in order to meet the increasing global food demands (FAO, 2012). However, it is important that growth in culture is not prioritised over potential environmental degradation as this would undermine efficient growth of the sector with potential knock on effects for other ventures, aquaculture included (Frankic and Hershner, 2003). Aquaculture and specifically pond aquaculture has previously been associated with environmental degradation owing to the increased intensification of practices, particularly in relation to feed application and water exchange activities (Naylor et al., 2000) This intensification can lead to increased levels of nutrients and decreased levels of dissolved oxygen , which may result in eutrophication if left unchecked. In temperate regions Phosphorus is considered to be the limiting nutrient for freshwater ponds and lakes (Scheffer, 1998), however in tropical pond culture this switches to Nitrogen (Boyd and Tucker, 1998). This results in the use of nitrogen based fertilisers to promote growth of phytoplankton in order to provide a constant supply of natural feed in extensive or semi intensive farming systems, particularly in the culture of tilapia.

Pond culture has been reported to follow some similar management practices including water exchange rates and feeding rates. For example it is assumed that in the Mekong Delta, Vietnam, fertilisation does not occur in pangasius culture (Pekar et al., 2002). However a study by Hedlund et al. (2003) reported inputs of nitrogen and phosphorus attributed to the increase production of livestock, fruit and vegetables on aquaculture sites, indicating a possible shift towards maximising the potential usage of land surrounding pangasius systems. High levels of water exchange are associated with pond aquaculture in most countries and has been shown to vary between species and country (Popma *et al*., 1995; Jackson *et al.,* 2003; Wahab *et al.,* 2003; Verdegem *et al*., 2006). Pangasius farms in the Mekong Delta have been known to exchange up to 50% of the pond water, daily (Phan *et al*., 2009). Whereas tilapia culture is thought to be less water exchange reliant at approximately 10% daily or even weekly (Verdegem, 2007)

The implementation of environmental models, which utilise a system dynamics approach can allow the effects of growth, with varying management practices, to be simulated and assist as a decision making tool for future farm management.

The models produced for this study have been developed based on farm level data collected for over 200 farms by the SEAT project (Murray et al, 2011) they were then further refined through data collected for sites, based on water management practices, which is further explained in the following chapter. This provides an interesting comparison between farming practices that occur on aquaculture sites. Although many studies have been carried out on nitrogen balances in ponds, these are typically based on a specific farm, assumed to be representative of the culture practices for whichever species is farmed. However this study investigates the variation of practices and their effect on the nutrient dynamics within the farm boundary. This allowed the models to produce simulations that result in comparable outputs to the practices occurring on farms. It is important to understand the implications that management practices have on not only the farm but the surrounding environment as it provides an indication of where changes can be made that may improve the quality of effluent that is discharged to the environment. This may in turn lead to increased sustainability of the aquaculture system and reduce the potential for eutrophication of natural water bodies used, in some cases by the same producers discharging into it as well as other stakeholders.

Environmental models can be developed in a number of ways, including from the ground up using coding and computing languages such as C++. However in recent years there has been an increase in the use of object based modelling programs, which allow models to be built through linked pre-coded objects, requiring that the user have a detailed understanding of the modelled system rather than the need to learn complex computer code.

The models developed in this chapter are aimed towards fish and shrimp production in ponds in SE Asia. The SEAT project is concentrated in four countries in SE Asia; Thailand, Vietnam, China and Bangladesh, and covers four of the major export species for the region (tilapia, shrimp, pangasius and prawn). As the SEAT initial scoping work showed most prawn to be cultured for domestic markets, this was not considered for the study. As a part of work package 4 (Environmental models) initial generalised models were developed, which are outlined below, for application to shrimp and fish culture in ponds. Keeping the models to a more general format for each culture group results in a wider application range, allowing the models to be used in any of the countries by simply changing some input parameters. The outputs of these models can then be used to develop action research objectives, which can investigate questions that are further raised by the modelling process (work package 9, SEAT)

## 3.3. Methodology

### 3.3.1 Modelling Software

The model was developed in the object-based based software Powersim Studio 8© (Powersim, Norway).This is a powerful business modelling software with an inbuilt language that is utilised through an object based system of flows of variables to and from levels, as shown in figure 3.1, to build a visual conceptual framework which can be easily understood and modified. This functional approach allows the user to focus on the processes occurring within the system under investigation while removing the need for learning complex computational languages. Powersim is considered an industry standard in business modelling due to its powerful capabilities and was therefore chosen as the core modelling software for this study.

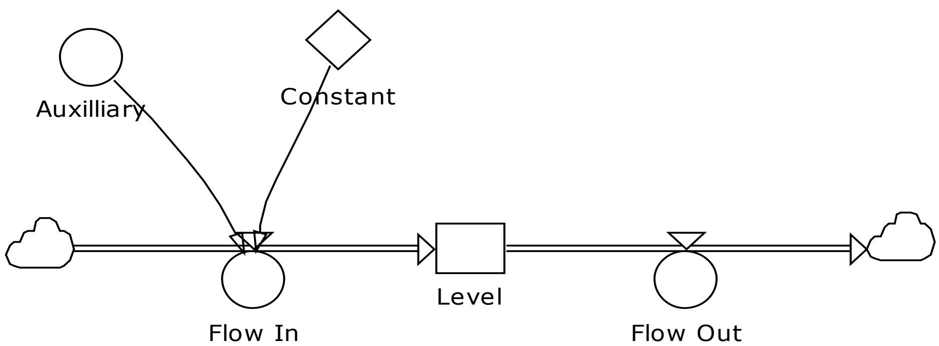



Figure 3.1: Powersim Studio 8© object based modelling system showing the major components used for the model construction process

### 3.3.2 Model Construction

The model simulates the fate of nutrients as shown in Figure 3.2 and is based on the basic mass balance and edited using relative literature information (Beveridge *et al.*, 2000). Outputs are based on a theoretical production of a fish species and shrimp, using an FCR of 1.7 and 1.9, respectively, as a standard using a time step of 1 day. (Verdegem and Bosma, 2009; Lebel et al., 2010)

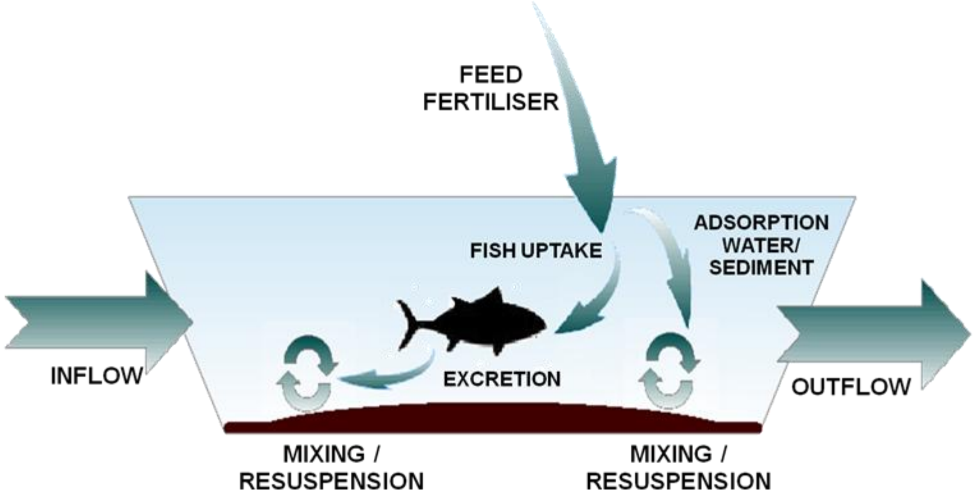



Figure 3.2: Fate of nutrients in a fish pond

Four major components of the model were identified and developed including a production, species and feed, sedimentation, water quality and dissolved oxygen module (fig 3.3). Each of these modules contains sub-modules which interact to provide the final outputs for each section investigated. The boundary of the initial model was set to pond level with the option to build up to farm level as a whole with outputs for individual ponds provided. Using a time step of 1 day the models were run over the course of an average culture cycle for both tilapia and shrimp at 6 months and 4 months respectively as implied from questionnaire-based survey data. Various data were gathered from both literature and survey work which was used to fill in the models interactions.

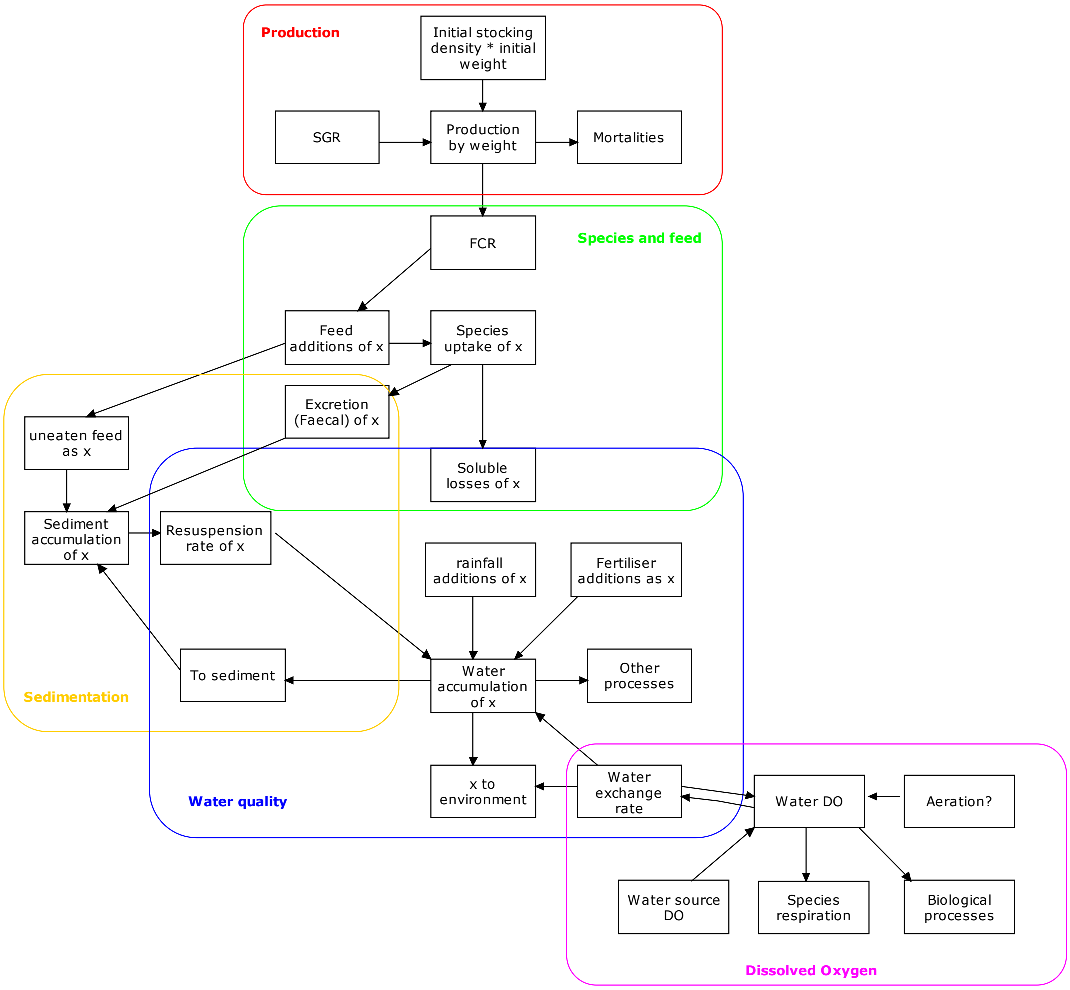



Figure 3.3: Conceptual diagram of the generic model showing the interactions between the different submodels, identified by the coloured frames

### 3.3.2.1 Production Submodel

The production module simulated the effect of growth versus mortality on production values for a pond system. The equations utilised are outlined in the appendix as is the conceptual model.

An initial value for the biomass in the pond was derived from the stocking density, taken as an average from the survey farms, multiplied by the pond area to give the number of individuals in the pond which was then multiplied by the individual weight of juvenile fish or shrimp to provide the overall initial biomass in the pond. The input of growth is defined using the SGR (Specific growth rate equation) as outlined by Hopkins (1992) by applying species specific values for the initial weight and stocking density of both the fish and shrimp, returning a growth rate in %/day as the input to the pond. The removal of biomass is accounted for by the rate of mortality, which was defined using average mortality values from the large integrated survey for each species. This provided an estimation of percentage loss over the whole cycle which was divided by the number of days in the production cycle to provide a percentage loss per day to the farm.

The production output from this module is then fed into the feeding process module to determine the uptake and deposition of nutrient x in feed stuff using the standardised FCR. (See appendix 2.1 and 2.2 for Powersim Diagram and equations)

#### 3.3.2.2 Species and feed submodel

The species and feed submodel determines the volume of feed added then follows the mass balance of its various end destinations of waste feed, assimilation by the species and excretion (both solid and dissolved). This particular set of equations is originally set to the tilapia mass balance in (Beveridge et al, 2000) with some adaptations to account for the processes actually occurring in the system. The model assumes an FCR of 1.7 for fish and 1.9 for shrimp at this stage as this is frequently reported for the respective species production in South East Asia (Verdegem and Bosma, 2009;Lebel et al., 2010). Consumption is assumed to be approximately 90% with a faecal loss based on a digestibility coefficients outlined in table 3.1 and 3.2. Uneaten feed and faeces produced are assumed to settle on the pond bottom, therefore adding to the sediment nutrient content. The outputs of dissolved losses from the module are used as an input for the water quality module explained later in this chapter. Powersim diagram and equations can be found in appendix 2.3, 2.4 and 2.5.

#### 3.3.2.3 Sedimentation submodel

Sedimentation is a vital part of the processes occurring within the pond ecosystem and has therefore been accounted for in the model. The additions to the sediment or sludge are generally assumed to be in the form of faecal matter excreted by the organism and waste feed. Resuspension plays a major role in the fate of nutrients added to ponds and was modelled by interpreting resuspension as a function of the production in the pond, for total nitrogen, as previous studies have concluded that weight or size of the fish is of importance when it comes to soil water interface processes (Breukelaar et al, 1994, Sheffer et al, 1998). In accordance with these findings, the model developed by Avnimelech et al. (1999) was utilised for the resuspension rate of matter on the pond bottom (85% of biomass in the pond). The phosphorus resuspension rate was much lower due to its high affinity for adsorption to muds and was taken to be 20% (Shimoda et al. 2005; Jiménez- Montealegre et al. 2002; Briggs and Funge-Smith. 1994). (See appendix 2.6, 2.7 and 2.8 for Powersim diagram and equations)

#### 3.3.2.5 Fertilisation submodel

Due to the different types of fertiliser used in pond aquaculture the main three have been conscripted into the model with an option to disregard fertilisation should the practice not occur. The fertilisers included in the model are various manures, Urea, NPK (Nitrogen, Phosphorus, and Potassium) and TSP (Triple Super Phosphate). The removal of nutrients added through fertilisation was attributed to biological breakdown processes, which occur naturally within pond waters. (See appendix 2.9, 2.10 and 2.11 for the Powersim diagram and equations)

#### 3.3.2.4 Water Quality submodel

As estimating changes and implications for management of water quality is the main purpose of investigation it would seem fitting for the previous models to make a significant contribution to the main body of the water quality submodel. The water quality submodel takes into account the nutrient content of the water source, including additions from rainfall and the water exchange activities that take place on the farm. The major removal of nutrients from the farm is attributed to biological breakdown and uptake activities and water exchange practices (Verdegem & Bosma, 2009). The modules described previously contribute to the inputs of nutrients to the water column in the form of dissolved outputs of nutrients from the mass balance and resuspension of nutrients from the sediments, with a new module developed for fertilisation inputs. The Powersim diagram and equations can be found in appendix 2.13, 2.14 and 2.15.

#### 3.3.2.6 Dissolved Oxygen submodel

Dissolved oxygen is a crucial factor in water quality determination, and was modelled as an indicator of water quality in the farming systems under investigation. The dissolved oxygen submodel is determined through the input of oxygen from source water and includes any effect that using methods of aeration has on the system, such as paddlewheel aeration, which is the most common method in South East Asia. Data from previous studies using paddle wheel aeration were used to apply an aeration coefficient to the model. This can be implemented using a switch function which allows the model to be used for farms with and without aeration as a water management practice. (See appendix 2.16 and 2.17 for Powersim diagram and equations)

### 3.3.3 Hypothetical farm parameters

A theoretical farm for both fish and shrimp was used in preliminary versions of the models in order to provide initial inputs. Each farm was based on a typical scenario of tilapia or shrimp farming in Thailand using data collected by the SEAT project and literature data to find the most common practices. The pond sizes for each farm were set to 1 ha with a depth of 1 m while applying a six month cycle to the fish simulation and a four month cycle to the shrimp. As previously mentioned in the chapter an FCR of 1.7 and 1.9 were applied to the fish and shrimp models respectively. Nutrient data were taken from literature such as feed content and source water content due to previous data being available from water quality studies (table 3.1). A water exchange rate of 15% per day was applied to the fish model, while the shrimp model used 10% every 10 days based on averaged data from the SEAT project.

**Table 3.1: Hypothetical fish farm parameters taken from SEAT data and literature**

| Parameter | Values for Nitrogen model | Values for Phosphorus model | Unit | Source |
|---|---|---|---|---|
| Length of a cycle | 6 | 6 | months | FAO, 2013 |
| Average initial weight | 30 | 30 | g | SRAC |
| Average harvest weight | 500 | 500 | g | FAO/SRAC |
| Pond area | 1 | 1 | ha | Assumed |
| Stocking density | 2 | 2 | Individuals/$m^2$ | Auburn Uni |
| Mortality rate | 25 | 25 | % | SRAC |
| Total feed added | 13002.96 | 13002.96 | kg | 1.7 FCR (Verdegem & Bosma, 2009) |
| Feed protein/phosphorus content | 32 | 1.4 | % | NRC 1993; Chowdhury *et al*, 2013 |
| Consumption coefficient | 90 | 90 | % | Assumed |
| Digestibility coefficient | 90 | 68 | % | Chowdhury *et al* 2013; Zhou & Yue, 2012 |
| Soluble loss | 36 | 0 | % | Schenider *et al*, 2005 |
| Total uneaten feed | Total feed added - Feed consumed | Total feed added - Feed consumed | | |
| Faecal addition | Feed Consumed -feed digested | Feed Consumed - feed digested | | |
| Resuspension rate | 81% | 20 | % | Avnimelech, 1999 |
| Fertiliser application (Manure/Urea/Chicken litter/TSP) | 0.102/0.00306/0.05/0.006 26 | - | kg/$m^2$/wk | FAO, 2012 |
| Manure nutrient content | 1.46 | 0.55 | % | Jackson, 1958 |

| | | | | |
|---|---|---|---|---|
| Urea nutrient content | 46 | - | % | Jackson, 1958 |
| Chicken Litter nutrient content | 2.75 | 2.46 | % | Jackson, 1958 |
| TSP nutrient content | - | 46 | % | Jackson, 1958 |
| Rainfall per month | array of monthly data | array of monthly data | mm | http://www.worldweatheronline.com |
| Total nutrient in rain | 0.77 | 0.04 | mg/l | Liljestrom *et al*, 2012 |
| Pond depth | 1 | 1 | m | Assumed |
| Total nutrient in source water | 1.51 | 0.56 | mg/l | Leelahakriengkrai & Peerapornpisal, 2011 |
| Water exchange | 15 | 15 | %/da | Popma & Lovshin, 1995; Verdegem, 2007 |
| Time between exchange activities | 1 | 1 | da | Popma & Lovshin, 1995; Verdegem, 2007 |
| Aeration addition coefficient (Aeration) | 4.7 | - | mg/l | Avnimelech *et al,* 1992 |
| Aeration addition coefficient (No aeration) | 0.5 | - | mg/l | Avnimelech *et al* 1992 |
| Source water DO content | 4.12 | - | mg/l | Leelahakriengkrai & Peerapornpisal, 2011 |
| Fish respiration coefficient | 22.5 | - | % | Boyd, 1985 |
| DO removal due to biological processes | 77.89 | - | % | Boyd, 1985 |

**Table 3.2: Hypothetical shrimp farm parameters taken from SEAT data and literature**

| Parameter | Values for Nitrogen model | Values for Phosphorus model | Unit | Source |
|---|---|---|---|---|
| Length of a cycle | 4 | 4 | months | FAO |
| Average initial weight | 7.318 | 7.318 | g | Saoud *et al*, 2003 |
| Average harvest weight | 30 | 30 | g | FAO |
| Pond Area | 1 | 1 | ha | Assumed |
| Stocking density | 33 | 33 | spp/$m^2$ | Jackson *et al*, 2003 |
| Mortality rate | 25 | 25 | % | SRAC, 1989 |
| Total feed added | 14567.74 | 14567.74 | kg | 1.9 FCR (Lebel *et al*., 2010) |
| Feed protein/phosphorus content | 32 | 1.4 | % | NRC 1993; Chowdhury *et al*, 2013 |
| Consumption coefficient | 90 | 90 | % | Assumed |
| Digestibility coefficient | 82.09 | 27.04 | % | Lin *et al*, 2004 |
| Soluble loss | 36 | 0 | % | Schenider *et al,* 2005 |
| Total uneaten feed | Total feed added- Feed consumed | Total feed added- Feed consumed | | |
| Faecal addition | Feed Consumed -feed digested | Feed Consumed - feed digested | | |
| Resuspension rate | 81% | 20 | % | Avnimelech, 1999 |
| Fertiliser application (Manure/Urea/Chicken litter/TSP) | 0.102/0.00306/0.05/0.0062 6 | - | kg/$m^2$/wk | FAO, 2012 |
| Manure nutrient content | 1.46 | 0.55 | % | Jackson, 1958 |
| Urea nutrient content | 46 | - | % | Jackson, 1958 |
| Chicken Litter nutrient content | 2.75 | 2.46 | % | Jackson, 1958 |
| TSP nutrient content | - | 46 | % | Jackson, 1958 |
| Rainfall per month | array of monthly data | array of monthly | mm | http://www.worldweatheronlin |

| | | | | |
|---|---|---|---|---|
| | | data | | e.com |
| Total nutrient in rain | 0.77 | 0.04 | mg/l | Liljestrom et al, 2012 |
| Pond depth | 1 | 1 | m | Assumed |
| Total nutrient in source water | 1.51 | 0.56 | mg/l | Leelahakriengkrai & Peerapornpisal, 2011 |
| Water exchange | 10 | 10 | %/da | Jackson et al, 2003 |
| time between exchange activities | 10 | 10 | da | Jackson et al, 2003 |
| Aeration addition coefficient (Aeration) | 4.7 | - | mg/l | Avnimelech et al, 1992 |
| Aeration addition coefficient (No aeration) | 0.5 | - | mg/l | Avnimelech et al 1992 |
| Source water DO content | 4.12 | - | mg/l | Leelahakriengkrai & Peerapornpisal, 2011 |
| Fish respiration coefficient | 0.115 | - | mg/l/hr | Anongponyoskun et al, 2012 |
| DO removal due to biological processes | 77.89 | - | % | Boyd, 1985 |

## 3.4. Fish model results

### 3.4.1 Production submodel results

The production levels of the hypothetical farm are estimated to be 7648.80 kg per cycle with an SGR of 1.56% and mortality rate of 25% of the total volume produced. Figure 3.4 shows the increase in production levels over the course of the production cycle, indicating an increase by a factor of 7.

The results from this model were used to provide the feed input to the fish nutrient uptake submodel in order to provide a total feed input of 13002.96Kg resulting from an FCR of 1.7, using the equation:

*Total feed added = Biomass produced * 1.7*

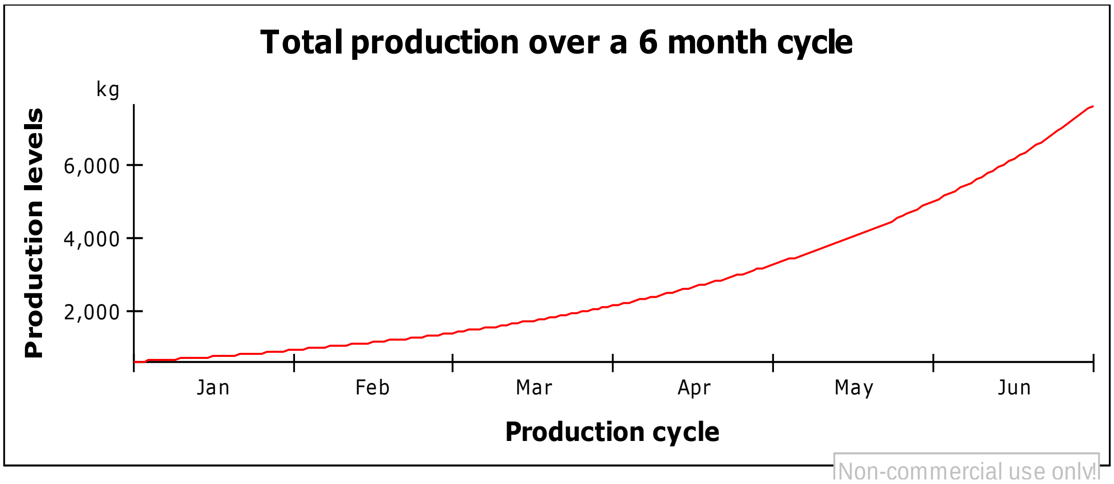



Figure 3.4: Powersim output graph showing the increasing rate of production over a 6 month production cycle for fish resulting in a maximum production in 1ha pond of 7648.80 kg

### 3.4.2 Water nutrient levels

The total nitrogen (TN) content in the water column of the pond shows an initial large increase due to the settling of the fish in the pond for the first 14 days of the cycle. This then decreases from 3.38 mg-N/l to 2.29 mg-N/l (Fig. 3.5) in connection with the introduction of a daily water exchange rate of 15%. This trend of increasing and decreasing nitrogen levels occurs throughout the cycle creating a relatively small flux in the level of nitrogen within the pond, and remains at least 1 mg-N/l above the source water levels. It should be noted that the total nitrogen level modelled remains below the limits outlined in the Better Aquaculture Practices (BAP) guidelines for most tropical fish culture species (GAA, 2008a).

The total Phosphorus (TP) levels modelled show an initial increase, likely due to the additions of feed and fertilisers without water exchange. However this shows a similar trend to TN as it dramatically decreases once water exchange is introduced. The graph shows an increasing trend in the level of TP over the course of the cycle, with fluctuations occurring daily due to the 15% daily water exchange rate applied to the farm (Fig. 3.6).

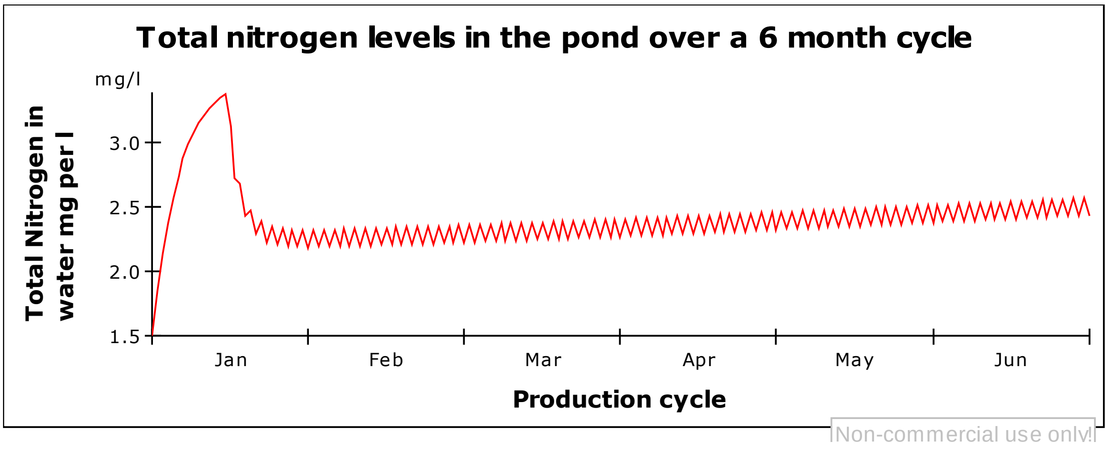



Figure 3.5: Total nitrogen levels over the course of a 6 month cycle in a fish pond

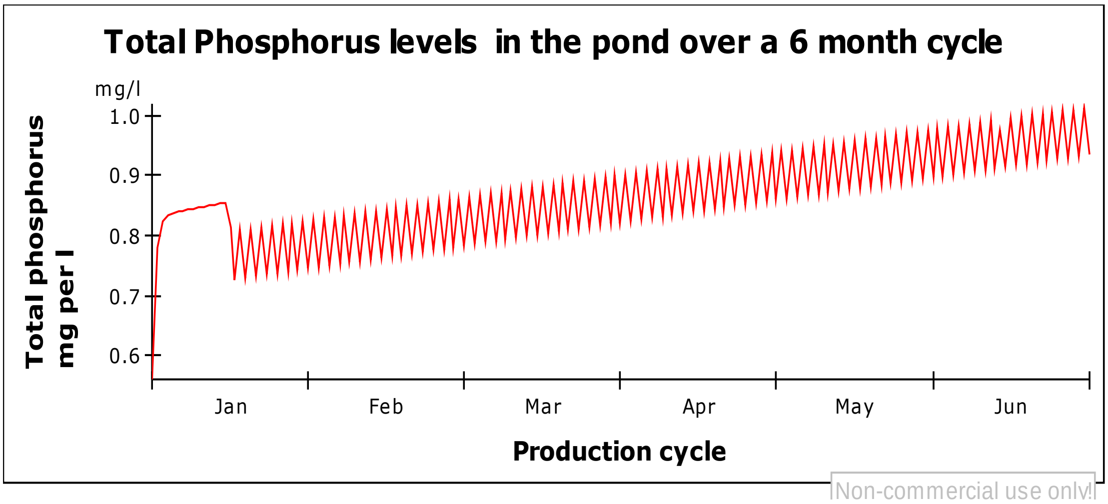



Figure 3.6: Fluctuation of TP in the pond water over the course of a 6 month production cycle in a fish pond

### 3.4.3 Sediment nutrient additions

The simulation indicates that the total nitrogen additions to the sediment amount to 197.10 kg-N over the course of a production cycle (Fig. 3.7). This is approximately 10% of the total input of nitrogen through feed, fertiliser and water. This is possibly due to breakdown mechanics that occur in the nitrogen cycle or possibly loss through seepage action, or a combination of the two. However calculated phosphorus input to the sediment shows a much higher level than reported for nitrogen, for the given level of fish production. It shows the additions of phosphorus to the sediment to be over 1096.37 kg, 79% of the total phosphorus input to the system, conforming to previously reported results (Verdegem, 2007) (Fig. 3.8)

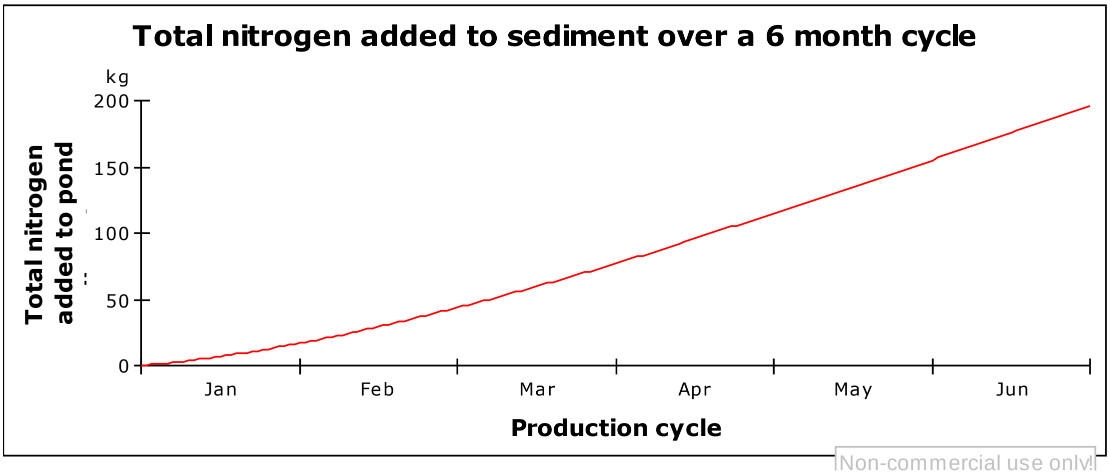



Figure 3.7: TN added to the sediment of a fish pond over the course of 6 months

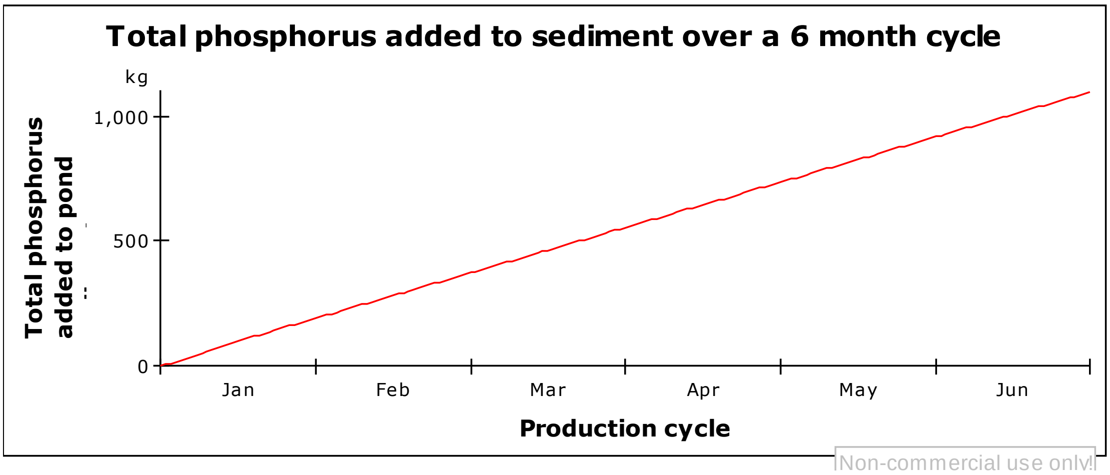



Figure 3.8: TP added to the sediment of a fish pond over the 6 month production cycle

### 3.4.4 Dissolved Oxygen levels

Assuming that aeration occurs within this system, using paddlewheels to promote mixing, the dissolved oxygen levels in the system shows an initial decrease. However with the introduction of fresh water from the source, DO levels show an increase again (fig. 3.9). This is possibly due to the more oxygenated surface waters being drained away leaving the deeper less well oxygenated water behind for a short while. The introduction of fresh water through flushing results in the mixing of the water, aiding the paddlewheel aerators to maintain an acceptable level of DO in the water. Although the level is less than the BAP (Better Aquaculture Practices) guidelines for good quality water (5.0mg/l) it does not fall to 3.0mg/l which is considered to be the lower limit for efficient growth in tropical pond aquaculture practices (Mjoun et al., 2010).

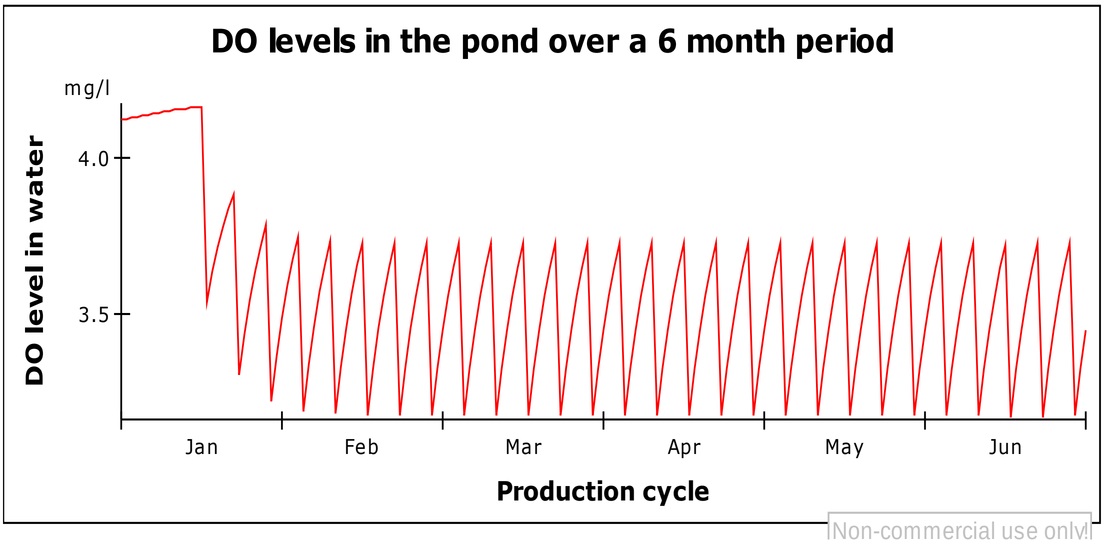



Figure 3.9: DO level in a fish pond over the course of a production cycle

## 3.5. Shrimp simulation results

### 3.5.1 Production submodel results

Due to a high stocking density used, assuming 25% mortality rate over the course of the production cycle, a total biomass of 7667.23 kg with an SGR of 1.17 %/day is estimated by the model (Fig. 3.10). This does not take into account any mass mortality events that may occur within shrimp populations. The total feed added to the system (assuming only commercial feed is used) amounted to 14567.74kg to achieve an FCR of 1.9.

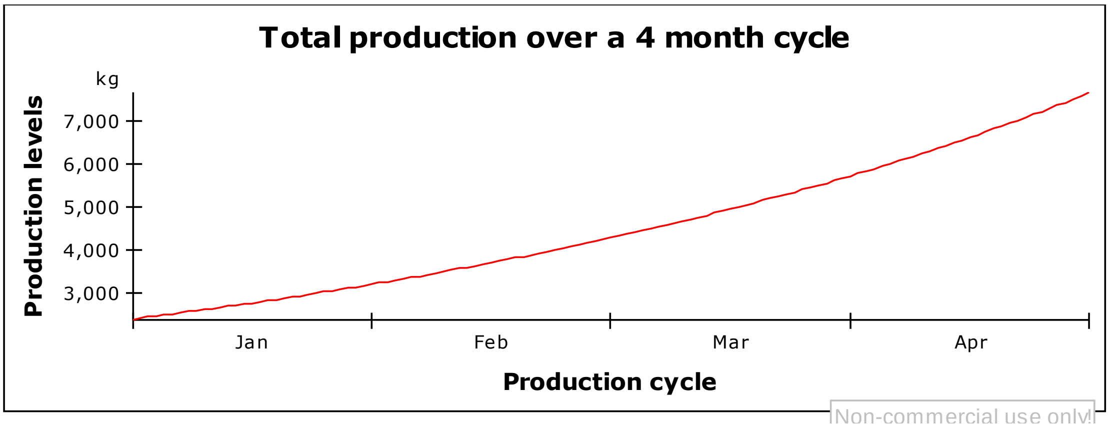



Figure 3.10: Total biomass produced in a 1ha pond at an SGR of 1.17 and mortality rate of 25%

### 3.5.2 Water nutrient levels

A Water exchange rate of 10% every 10 days was applied to the model. The simulation shows the effect the water exchange activities have on the water column nutrient content. Both TN and TP show an increase in levels between the exchange days (Fig 3.11 & 3.12), albeit not steadily. Results for TN indicates an initial increase in nutrients, likely from the top up waters, however there is also the small increase shown between water exchange activities possibly attributed to the ongoing additions of feed and fertilisers. TP shows a much more dynamic relationship with the water column with a sudden drop after the top up of water. Likely due to the settling of phosphorus in the sediments, which can be disturbed by foraging shrimp. The two sets of simulation outputs show that the TN levels reach 4.37mg/l which is close to the standards outlined by Better Aquaculture practices, whereas TP is shown to exceed the BAP guidelines of 0.5 mg/l, reaching a high of 1.1 mg/l (GAA, 2008b).

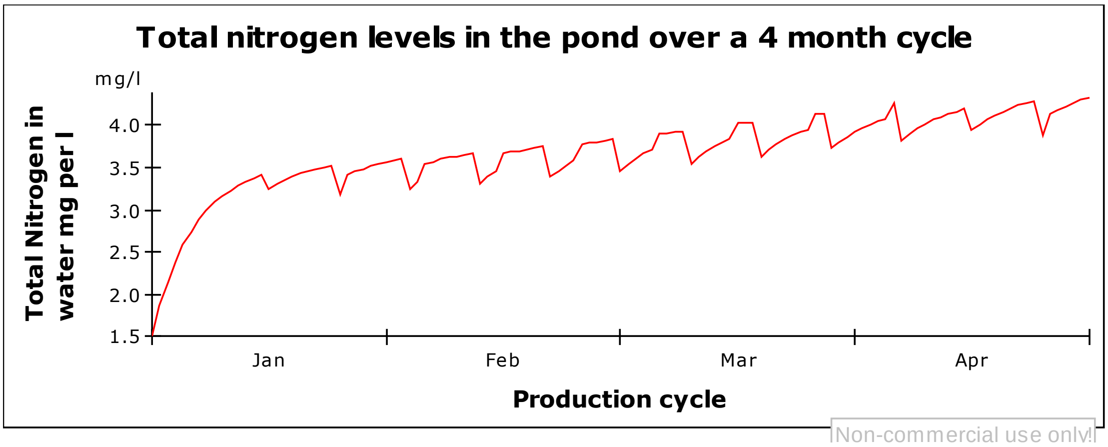



Figure 3.11: Total Nitrogen fluctuations over the 4 month cycle in the shrimp pond

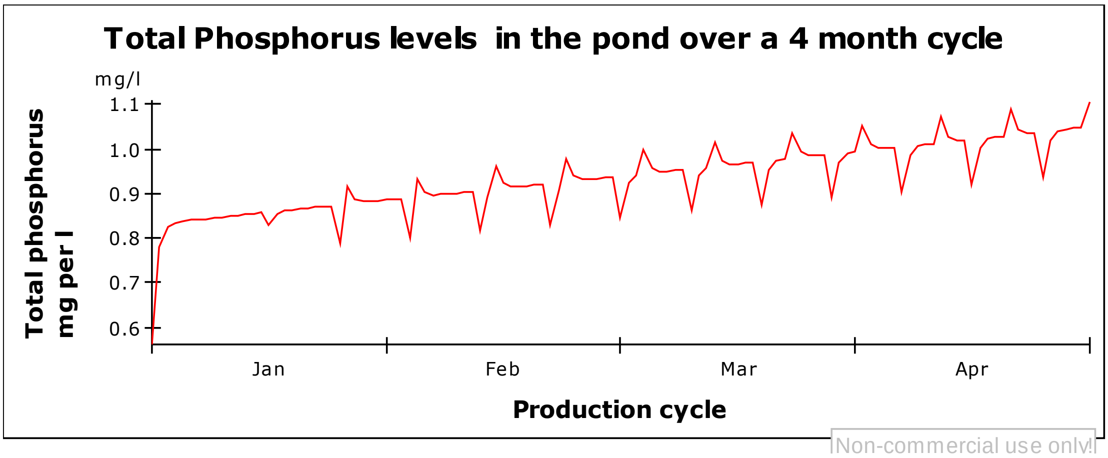



Figure 3.12: Total Phosphorus levels over the 4 month cycle in a shrimp pond

### 3.5.3 Sediment nutrient additions

Total nitrogen and phosphorus added to the sediment differ in mass at 209.28kg (Fig. 3.13) and 835.45kg (Fig. 3.14) respectively.

Resuspension also plays a large part in the lower levels of nitrogen in the sediments. Shrimp are well documented foragers (Tucker and Hargreaves, 2012) and facilitate greater levels of resuspension of particles into the water column through moving around on the pond bottom. This however is less of an issue for TP as phosphorus has an affinity to bind with the sediment becoming trapped in the pond bottom indicated in the model as 86.1 % of TP added to the system from feeds and fertiliser is found in the sediment. Although some TP may become resuspended in the water column, the lower amount is likely due to the lower concentrations added to the system.

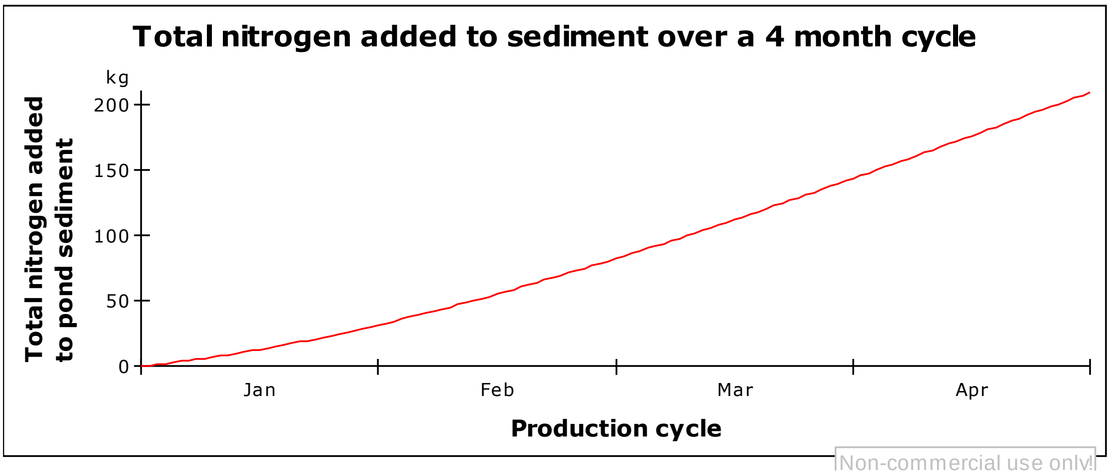



Figure 3.13: Total amount of TN added to sediment in a shrimp pond over the course of a production cycle

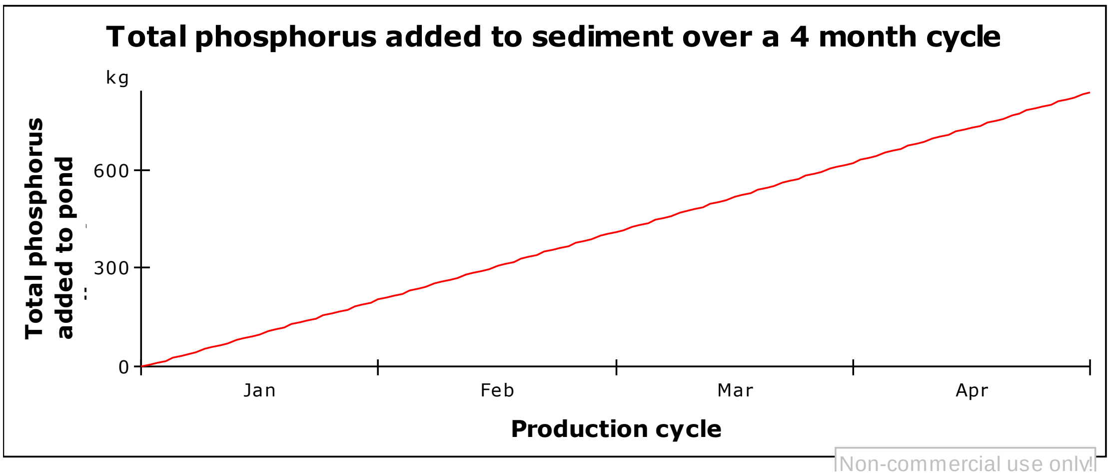



Figure 3.14: TP added to the sediment of a shrimp pond over the course of a production cycle.

### 3.5.4 Dissolved Oxygen levels

Even with the use of aerators in the shrimp pond there is a decrease in the DO levels. This is interesting as it suggests that without the aerators the water DO levels would drop dangerously low for the shrimp resulting in reduced growth. The total drop in the level in the ponds over the course of the four month cycle amounts to 0.92mg/l. The model output shows a larger drop of DO in the days where water exchange takes place, however this never reaches below 3.4 mg/l (fig. 3.15), which is acceptable as it does not drop to below 3mg/l recommended as the lower limit of DO for most aquaculture practices.

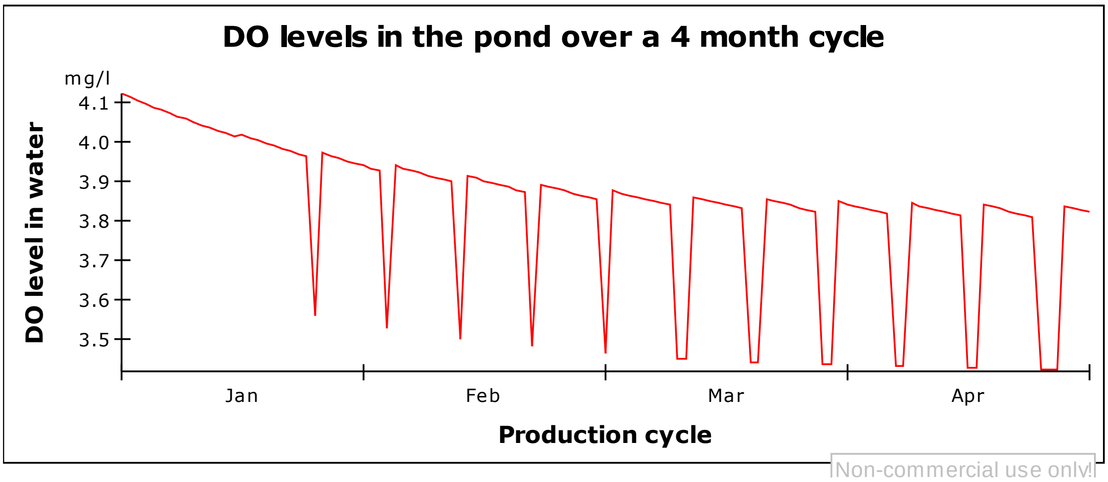



Figure 3.15: Dissolved oxygen level (mg/l) over the course of the shrimp production cycle using paddlewheel aerators.

## 3.6. Sensitivity Analysis

A sensitivity analysis was carried out on the model to determine which parameters have greatest impact on the model. This provides an indication of the reliability of the models in relation to fluctuations of relatively small parameter changes. Table 3.3 shows the results of the sensitivity analysis. It is shown that fertiliser input has an important impact on the model for both TN and TP and that water exchange has a significant effect on the level of nutrients in the water in comparison to the other parameters. While feed application has a higher impact on the TN in the sediment, it should be noted that the application of feed to the system has a similar influence on TN in the water column as the TN level in the supply water. These finding suggest that TN is highly influenced by farm management practices, which is not unknown; however the implication that water management has a higher impact than feed input on the water is of interest. TP is less affected by the feed inputs than that of TN levels; this is likely due to the lower concentration of TP in the feed to begin with. It is suggested in the results that largest source of TP is from fertilisers followed by the water source. These results indicate that improving the efficiency of management practices may be beneficial in reducing the nutrient content of the farm water and sediment

**Table 3.3: Sensitivity analysis of the model showing the percentage change in the outputs utilising a +/- 10% change in the forcing factors**

| Parameter | % change | TN in water | TN in sediment | TP in water | TP in sediment |
|---|---|---|---|---|---|
| Stocking density | 10% | 0.00% | 1.3% | 0.00% | 0.00% |
| | -10% | 0.04% | 1.7% | 0.00% | 0.00% |
| Mortality | 10% | 0.00% | 0.10% | 0.00% | 0.00% |
| | -10% | 0.00% | -0.10% | 0.00% | 0.00% |
| Total feed added | 10% | 1.25% | 10% | 0.00% | 0.06% |
| | -10% | 1.25% | 10% | 0.00% | 0.06% |
| Water exchange | 10% | -3.50% | 0.00% | -1.90% | -1% |
| | -10% | 3.79% | 0.00% | 1.90% | 1% |
| Fertilisers | 10% | 7.60% | 0.00% | 9.75% | 9.29% |
| | -10% | -7.60% | 0.00% | -9.86% | -9.40% |
| x in supply water | 10% | 1.13% | 0.00% | 0.14% | 0.59% |
| | -10% | 1.17% | 0.00% | -0.14% | -0.56% |
| Supply water DO | 10% | 3.70% | | | |
| | -10% | 3.50% | | | |

## 3.7. Discussion

This study has focused on the construction of models for both fish and shrimp in pond culture conditions. They have investigated the full activities that are practiced in each and provided outputs based on both previous and current studies. Many models focus on a specific relationship in the aquaculture sector such as Carbon and Nitrogen levels in relation to different feed types (Riche et al., 2001; Maina et al., 2002) or dissolved oxygen levels in relation to the time of day and the phytoplankton activity (Culberson and Piedrahita, 1996; Ebeling et al ,2006) This model takes all of the major activities known to exist in pond aquaculture in South East Asia and forms an output based on all of these activities taking place as they occur, providing a holistic look at the nutrient and dissolved oxygen levels within each farm.

The fish model showed a production value of 7648.80 with an SGR of 1.56%/day, this is considered to be an acceptable level for an SGR in literature for fish (Yakubu et al., 2012; EL-Sayed, 2006). The feed input for the farm was set to 1.7 according to Verdegem and Bosma (2009) resulting in outputs of TN and TP in water of 2.29 mg/l and 0.94 mg/l respectively. Previous studies of fish ponds in SE Asia suggest the nutrient levels vary greatly with lows of 0.16mg/l and highs of 40mg/l previously recorded (Diana et al., 1991; Siddiqui and Al-harbi, 1999). The sediment TP levels shown in the model conforms to previous studies by Verdegem (2007) where the much of the phosphorus added to the system is accumulated in the sediment (79%), this however was not the case for TN showing only 10% of the additions taken up in sediments. A possible reason for this is the action of phytoplankton and other factors breaking the nutrient down into other components, not described in the model.

The DO level shown in the fish model fluctuates throughout the cycle, attributed to the water exchange activities. Although the fluctuations are shown, the, maximum and minimum values stay relatively steady throughout the cycle after, what appears to be, a one month stabilisation period. As the model does not take into account the diurnal DO fluctuations it is possible the results rely too heavily on water exchange.

The output for the shrimp production model showed 7667.23kg produced over a four month cycle, with an SGR of 1.17%/day. An FCR of 1.9 was applied to the output from the production submodel as indicated by Lebel *at al*. (2010). This combined with a water exchange rate of 10% every 10 days resulted in TN and TP levels of 4.37mg/l and 1.1mg/l in the water, which are higher than that reported by Jackson *et al*. (2003). The shrimp model shows a similar behaviour to the fish model in relation to nutrient accumulation in the sediment. TN shows less accumulation as a percentage of the total TN added to the system (14%) than that of TP (86.1%). While the TP accumulation again conforms to literature findings (Wahab et al., 2003) the TN level appears lower. Possible explanation of this result may be the foraging action resulting in more TN available for other processes in the water column, i.e., uptake by phytoplankton or breakdown by microorganisms (Boyd and Tucker, 1998).

The DO level for shrimp ponds should remain above 3mg/l in order to promote efficient growth (McGraw et al., 2001). The model outputs suggest a level of 3.9mg/l. This is low though higher than that of the fish output.

The behaviours of various mediums in aquaculture pond systems have been investigated using dynamic models in this chapter. The results indicate that the fish pond has better quality water than that of shrimp farms as the TN and TP levels in the fish pond model are lower than that of shrimp. When compared to the Better Aquaculture Practices (BAPs) outlined by the GAA (2008a; 2008b) both farms are within the limits for TN (5mg/l), though the shrimp pond is 1mg/l from exceeding, whereas both farms exceed the limits for TP (0.05mg/l). However the shrimp farm is closest to the BAP guideline of 4mg/l minimum for DO followed by the fish farm.

Dynamic models such as those outlined in this chapter have the potential to become more heavily relied on for certification purposes, reducing the need to collect large data sets in order to determine if farms meet industry guidelines. Although the models outlined in this chapter are set to fish and shrimp in a generalised manner, there is the potential to adapt them further to become applicable to specific species under pond culture conditions.

# CHAPTER 4

# THE USE OF MULTIVARIATE STATISTICAL METHODS, TO LIMIT BIAS OF PRE EXISTING SITE SELECTION WITHIN THE SCOPE OF A LARGE-SCALE PROJECT.

## 4.1 Introduction

Site selection is an important part of research planning and should not be approached lightly. Questions are often raised regarding the relevance of sites selected in research studies, particularly in multidisciplinary projects. It is easy to randomly select from large groups of sites, however it should be considered whether straightforward random selection is the best method of providing sites to best fit the study. Much of research requires sites that fit certain criteria. For example a study into the effect of mangroves on aquaculture effluents requires an aquaculture farm to be located near a mangrove. A farm in an urbanised area will not meet the criteria for the study.

It is however difficult to do this in an objective manner. The previous example has a prejudgement on the site. It must be near a mangrove forest.

Commonly a significant proportion of sites are chosen based on a single variable then randomly selected in order to minimise the impact of any bias that may occur (Ruxton and Colegrave, 2003). Limiting choice based on a single variable can result in the elimination of variables that may have more impact on the site selection process than initially assumed (Fowler et al, 1998).

Much of the time, site selection for survey work for aquaculture development is based on locations defined using a multi-stage method, which utilises data obtained from local government sources (SEAT, 2013). Although this provides an area where the activities studied are predominantly carried out , it can result in exclusions of large areas of sites that may be of interest to the study.

It is possible to apply a sampling location based site selection method which is random and will reduce any bias introduced from pre selection of sites. Pham (2012) applied a stratified random approach to site selection in the Mekong delta in Vietnam to study the effect of agricultural pesticide use on aquaculture systems. He applied a set of random GPS points all over the Mekong delta and used GIS and image processing software, IDRISI, to randomly select points within the original selection and chose agriculture farms nearest to the points provided to study. The outputs of the models produced predict pesticide flow through the aquatic system.

The SEAT project is a major EU project which encompasses many subject areas including environmental impact, social impacts, ethics and an overall LCA (SEAT, 2012). The project is concentrated in four countries in South East Asia, namely, Thailand, Vietnam, China and Bangladesh. It is further divided into the major species identified for export, by the projects initial scoping study. The main species identified include; tilapia (mostly *Oreochromis niloticus*), catfish (*Pangasianodon hypothalamus*), shrimp species (*Penaeus monodon* and *Penaeus vannemei*) and freshwater prawns (*Macrobrachium rosenbergii*) (Phan et al, 2011). Both the scale and number of participating groups have made the aligning of site selection slightly more difficult as there are many different requirements from sites. A top down gradient approach was used by the project by allowing the participants who require the largest number of farms to select first followed by the next largest, selecting as closely as possible from the previous site selection.

Multivariate analysis is popular to define similarities between specific types of data without placing emphasis on one particular parameter (Afifi, 2012). This method tends to be utilised when a system or subject requires classification (Burton et al, 1991). Specifically, CA (correspondence Analysis) is popular in ecological studies of species data due to its unique ability to define species based on niche-specific parameters (Van Den Brink, 2003). It has been used in aquaculture research to define relationships between a multitude of effectors such as stocking density and its relationship with cage farmed salmon welfare, using Principal component analysis (Turnbull et al, 2005). Both Nhan et al (2006) and Mustafizur Rahman et al (2008) used multivariate analysis on pond aquaculture systems to investigate the effect of various inputs on water quality in pond aquaculture. Ordination methods are a popular method of analysis used in investigations as they indicate similarities between the data under scrutiny (Digby, 1987). Rarely is it used in a site selection capacity as randomisation of points or clustering is usually the favoured method.

The aim of this chapter is to outline the reasoning behind the use of multivariate analytical techniques for site selection purposes within a large integrated project and to show the outcome of the multivariate analysis resulting in the sites selected for in depth analysis. The analysis carried out will be used to classify the sites on the basis of water management data then ranked based on a top down approach to ranking the sites in preference.

## 4.2 Methods

Site selection for the overall project was defined using a multistage approach. (Murray and Little, 2012). Using data available from government offices in each country, locations of clusters of aquaculture sites were identified and the dominant areas of farms were chosen for further study. (Figure 4.1)

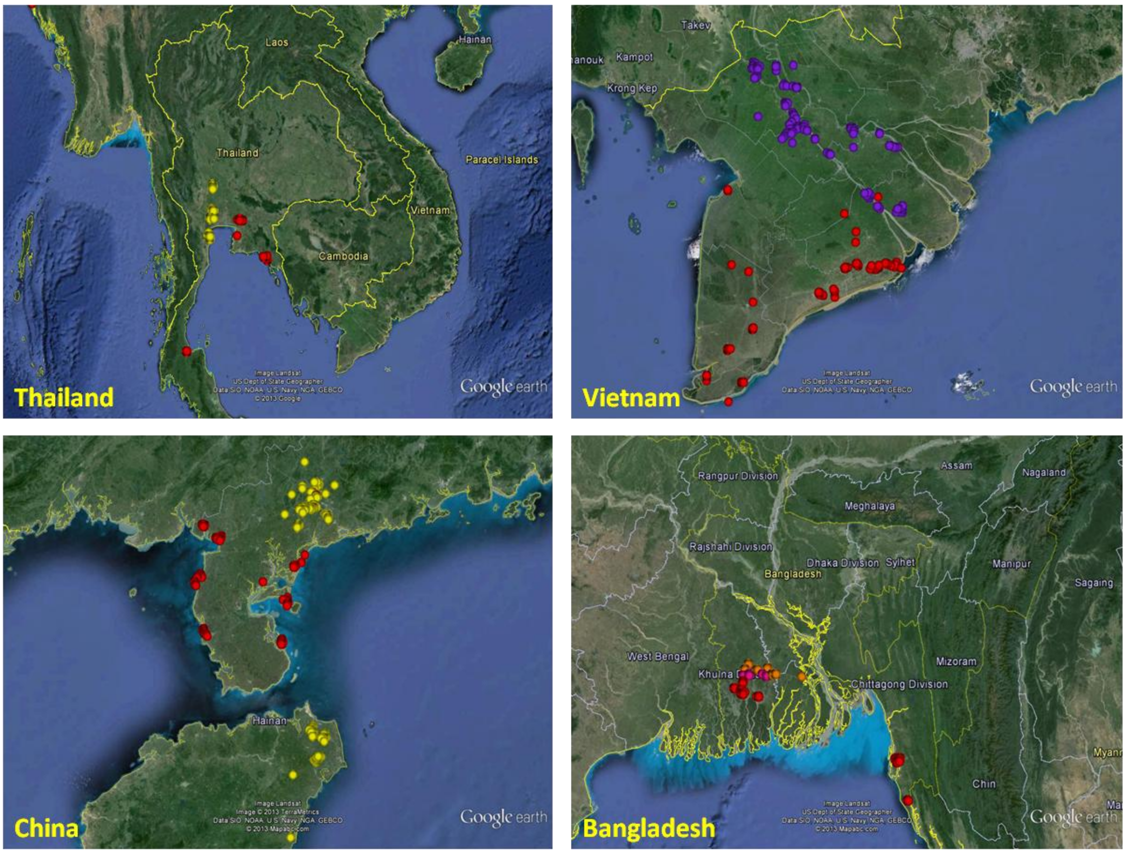



Figure 4.1: clusters of sites in each country for each export species (Yellow- tilapia, Red- Shrimp, Purple- pangasius, Orange- prawn, Pink- both; Bangladesh only)

The sites were based on clusters of the main producing areas in each country, which were determined through the use of national data, local officials and key informants in each area.

Data for the SEAT project was initially collected using large integrated surveys, posing questions relating to aquaculture farming activities and infrastructure in the four countries in SE Asia including Thailand, Vietnam, China and Bangladesh. The farming systems covered a large variety of farms from Intensive to extensive for the major producer species in each of the countries;

shrimp, tilapia, pangasius catfish and prawn. The cluster method used for initial site selection introduces a bias on the location of the farms, however in order to limit the effect of the bias on the site selection for future modelling efforts a multivariate analysis was carried out on the data collected from the surveys, in order to determine if there are distinct groups of farms based solely on water management practices, which will impact the water quality either positively or negatively.

Responses from the Farmer survey were recorded on a database for further data analysis and query. Water management responses from the survey questionnaire were used for the analysis, in this study, as these activities have the potential to drastically affect the surrounding environment's water quality. Each question in the survey had a list of answers to be selected from, which were determined by the scoping survey and communication with the in country partners. A matrix of farm number to question answers was created in Microsoft Excel with every answer possible in the first column and every farm number for a species used as a column header. Each species in each country was assigned an excel sheet of its own. The matrix was then completed by assigning a 1 (Yes) or leaving a cell blank (No) to every answer for each farm thus converting the data set to a binary format (Figure 4.2).

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Farm | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 2 | Pumped ground water | | | | | | | | | | | | |
| 3 | River-stream | | | | | | | | | | | | |
| 4 | Lake or reservoir | | | | | | | | | | | | |
| 5 | Primary irrigation canal | | | 1 | 1 | | 1 | 1 | | | | | |
| 6 | Secondary irrigation canal | | | | | | | | | | | | |
| 7 | Full strength coastal seawater | 1 | 1 | | | 1 | | | 1 | 1 | 1 | | |
| 8 | natural canal | | | | | | | | | | | | |
| 9 | not willing to respond | | | | | | | | | | | | |
| 10 | None | | | | | | | | | | | | |
| 11 | Storage in culture ponds before stocking | 1 | 1 | | 1 | | | 1 | | | | | |
| 12 | Settle pond(s) for inlet water only | | | 1 | | 1 | | | 1 | | | | |
| 13 | Settle pond(s) for both in & eff treat | | | | | | | | | | | | |
| 14 | Settle pond(s) for alt in & eff treat | | | | | | | | | | | | |
| 15 | Storage in culture ponds and settle ponds | | | | | | | | | | | | |
| 16 | storage in fish pond | | | | | | | | | | | | |
| 17 | not willing to respond | | | | | | 1 | | | | | | |
| 18 | Min storage days >10 | | | | | | | | | | | | |
| 19 | Reserc none | | 1 | 1 | 1 | | | | | | | | |
| 20 | Reserc partial | 1 | | | | 1 | 1 | | | | | | |
| 21 | Reserc full | | | | | | | | | | | | |
| 22 | not willing to respond | | | | | | | | | | | | |
| 23 | WE topup | | | | | | | | | | | | |
| 24 | WE full | 1 | | | | | | | | | | | |
| 25 | NA | | | | | | | | | | | | |
| 26 | not willing to respond | | 1 | 1 | 1 | | | | | | | | |
| 27 | Exch At maximal stocking density | | | | | | | | | | | | |
| 28 | Exch Averaged over the whole cycle | 1 | 1 | 1 | 1 | | | | | | | | |

Figure 4.2: An example of the layout of an excel sheet for the conversion of the survey data to binary format with the farm numbers in the first row and the answers to the survey in the first column

A cluster analysis was applied to the data set using the Jaccards coefficient using the Multi Variate Statistical Package (MVSP) (Kovach computing services, Wales) The cluster analysis establishes the presence of groups of similar parameters where none are predefined (Saracli *et al.,* 2013). Jaccards coefficient (shown below) was applied to the data as it particularly analyses binary data and not counts and scores (Niwattanakul *et al*., 2013). It is one of the simplest coefficients used in multivariate analysis techniques however provides a powerful visual output in the form of a dendogram, which in this case was used to determine similarity of water management practices in each country for each species and not to determine the effect of one set of parameters on another.

**Jaccards coefficient:**

$$S_{ij} = p/(p+q+r)$$

*P= number of variables positive for both objects*
*Q= the number of variables positive for the ith and negative for the jth objects*
*R= the number of variables negative for the ith and positive for the jth objects*
*S= the number of variables that are negative for both*

In the resulting dendograms the Jaccard coefficient cut off point was set to select predefined number of groups to enable differentiation between the number of case study sites. This use of multivariate analysis is subjective and was used to provide an optimal and manageable number of groups for the next stage of the study. Fuller *et al*., used this method to select marine conservation sites based on species abundance data resulting in a precedent for the use of multivariate analysis in a subjective manner.  The actual case study sites were then randomly selected from each group defined by the cluster analysis.

When working in large research projects it is important to keep sites as closely linked as possibly to contextualise any outcomes from different groups working within the project (MEXT, 2012). This was done using a graduated approach with the user requiring the largest number of sites selecting the primary farms to be used as a guide for the remaining users, down to the user requiring the least number of farms.

The selection process for the refined sites for WP4 was carried out using randomisation of sites in each groups provided by the Multivariate analysis, which were then ranked by the number of groups it crosses over; the highest rank covered the most groups and the lowest covered fewest. This was used as the guideline for site selection as there was the possibility that some farmers may not wish to participate in further research.

## 4.3 Results

The cluster analysis produced dendograms of groups of farms for each species in each country. Using the Jaccards coefficient, groupings of farms by water management practices was carried out.

### 4.3.1 Thailand

#### 4.3.1.1 Tilapia

The results for tilapia culture in Thailand produced 3 major groups at a distance of approximately 0.2 on the Jaccquard scale (Fig.4.2). This was taken to be the distinct groupings used for the differentiation of the water management practices used on the farm. Three groups were produced from the survey data, suggesting that there are 3 three potential water management characteristics involved in the Thai tilapia industry.

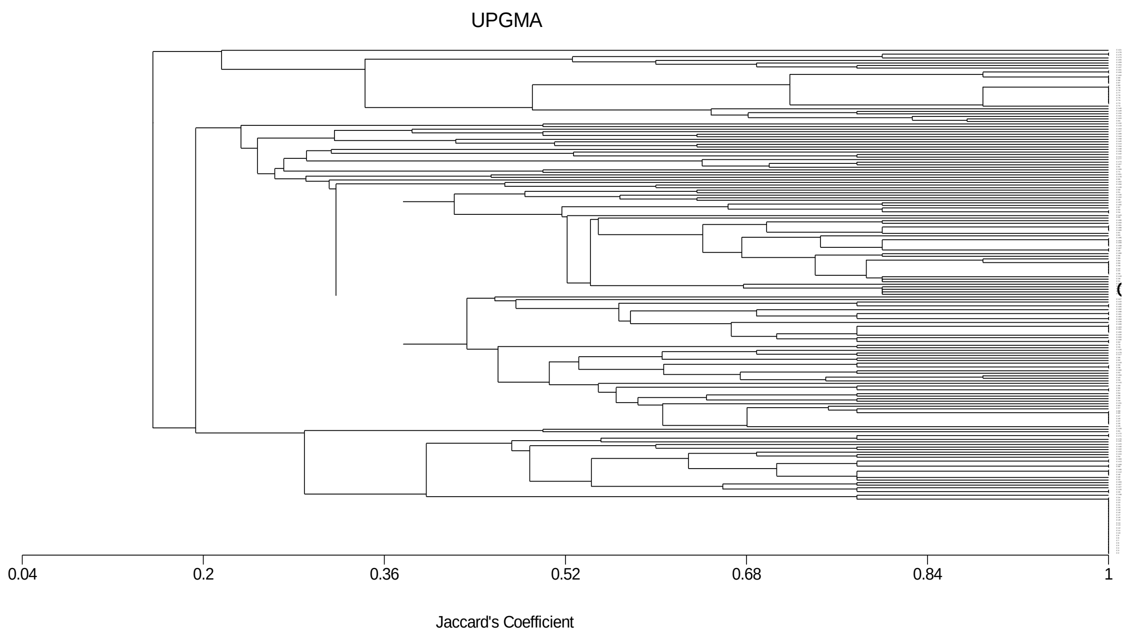



Figure 4.3: Dendogram showing the similarity between tilapia sites identified in Thailand

#### 4.3.1.2 Shrimp

The dendogram produced in figure 4.3 for shrimp farming in Thailand showed no distinct grouping at the 0.2 distance however at 0.3 there are 4 groupings, which were used due to their closer similarity than the full distance run. The top group was deemed an outlier and disregarded due to the presence of fewer than 10 farms in the grouping. This resulted in groups of farms which were more closely related in relation to water management practices.

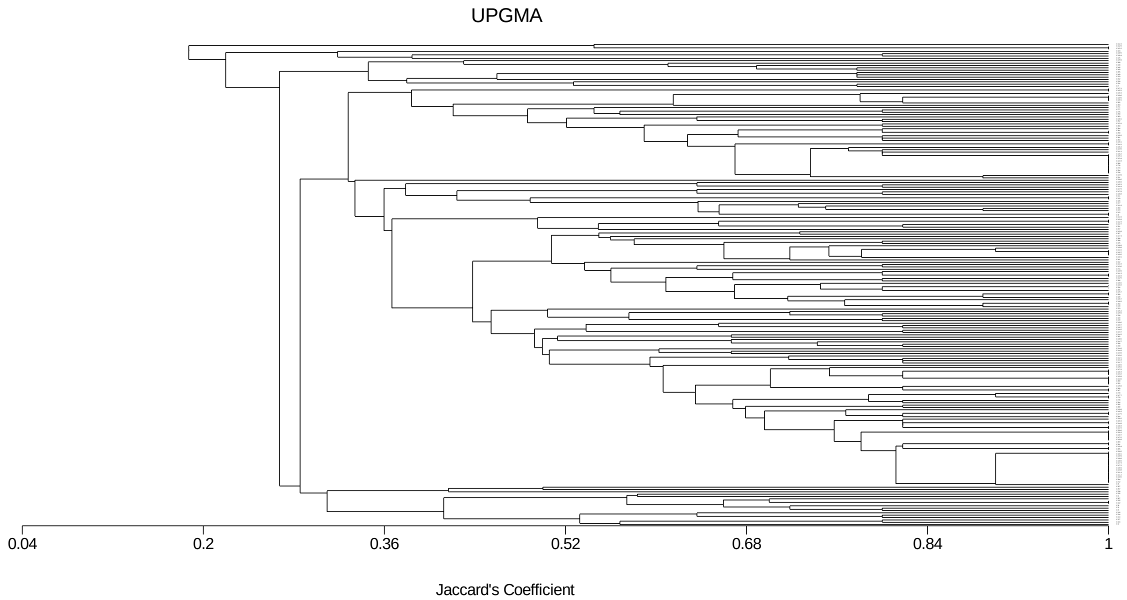



Figure 4.4: Dendogram showing the similarity between shrimp sites identified in Thailand

### 4.3.2. Vietnam

#### 4.3.2.1 Pangasius

The dendorgrams produced for Vietnamese pangasius farming (figure 4.4) show little divergence, however due to the tightness of the dendogram further along the scale, the second split at 0.4 was used to show if any differences in the practices provide differing outputs at model level. This resulted in 3 groups defined by water management practices suggesting either a move from or to the main practices currently applied.

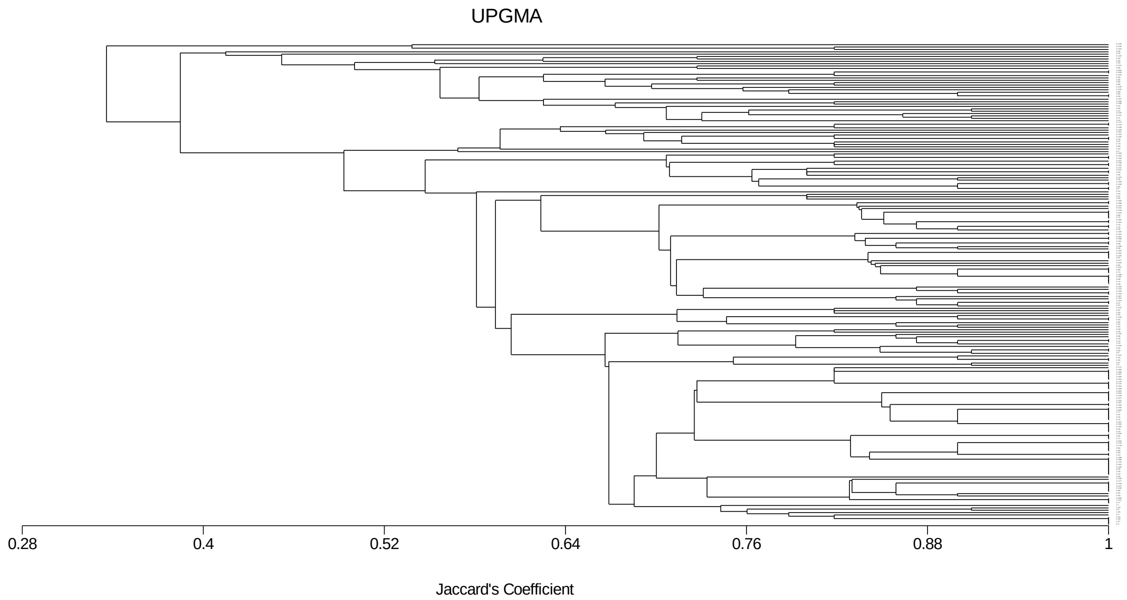



Figure 4.5: Dendogram showing the similarity between pangasius sites identified in the Mekong Delta, Vietnam

#### 4.3.2.2 Shrimp

The results for shrimp in Vietnam (figure 4.5) show even less difference between water management practices in the industry. The major group was then considered at a point of 0.48 in 3 distinct groups with more than 10 farms contained. Two further groups were available, however with less than 10 farms in one and less than 5 in the other they were disregarded as representative of the practices in the industry.

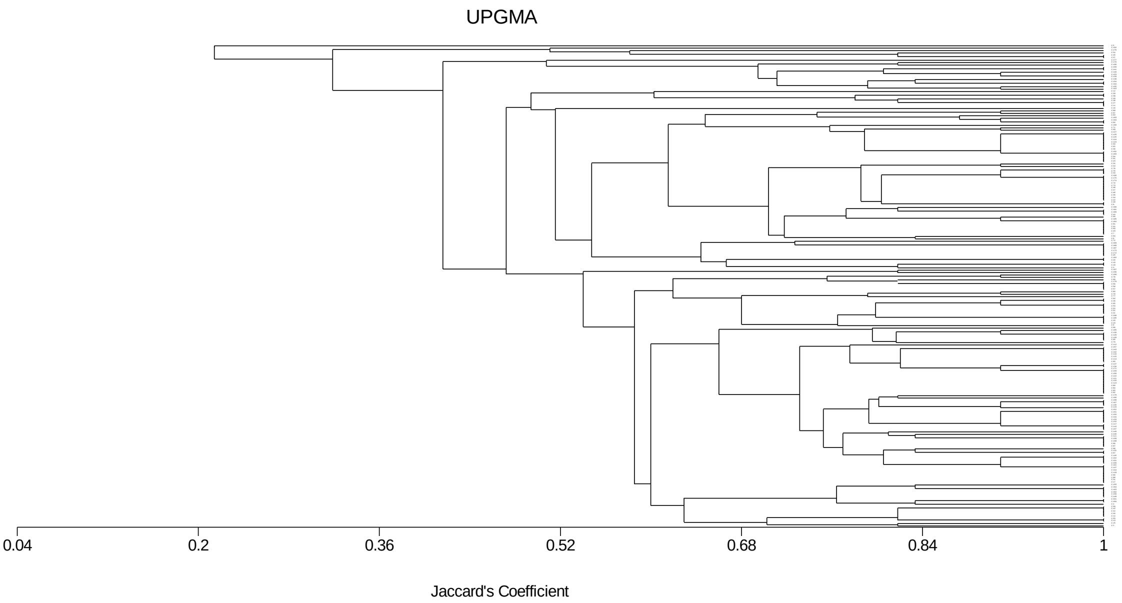



Figure 4.6: Dendogram showing the similarity between shrimp sites identified in the Mekong Delta, Vietnam

### 4.3.3 China

China provided little differentiation in the water management practices for either shrimp or tilapia (Figure 4.6 & 4.7).

#### 4.3.3.1 Shrimp

At a glance the dendogram suggests there is little difference between the management practices occurring in China however using the cut off of 0.4 on the Jaccard similarity scale, a generous number of groups with some significant differences in their practices were made apparent. The three largest groups from figure 4.6 were selected for further study within the SEAT project.

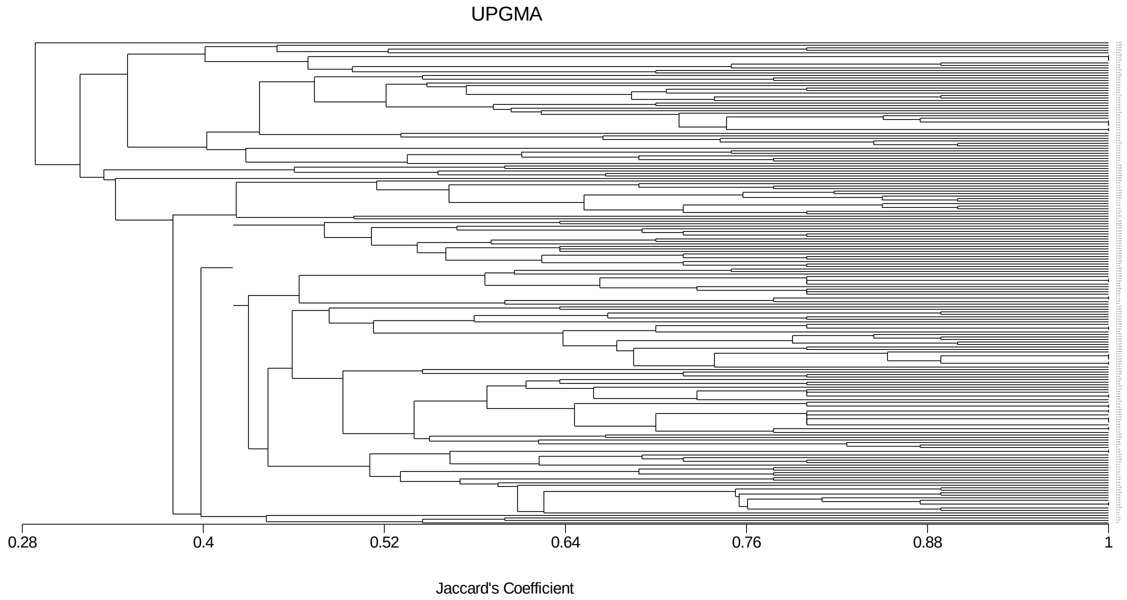



Figure 4.7: Dendogram showing the similarity between shrimp sites identified in Guangdong province, China

### 4.3.3.2 Chinese tilapia

Diagram 4.7 shows the dendograms for tilapia water management practices in China. The output shows little differentiation between the farms; therefore in order to provide a range of farms for the SEAT project a Jaccard's coefficient of 0.35 was used. This results in two obvious groups of water management practices within the sites with a number of much smaller groups identified. The two largest groups were taken from the smaller groups as the range of farms in each was 1-30.

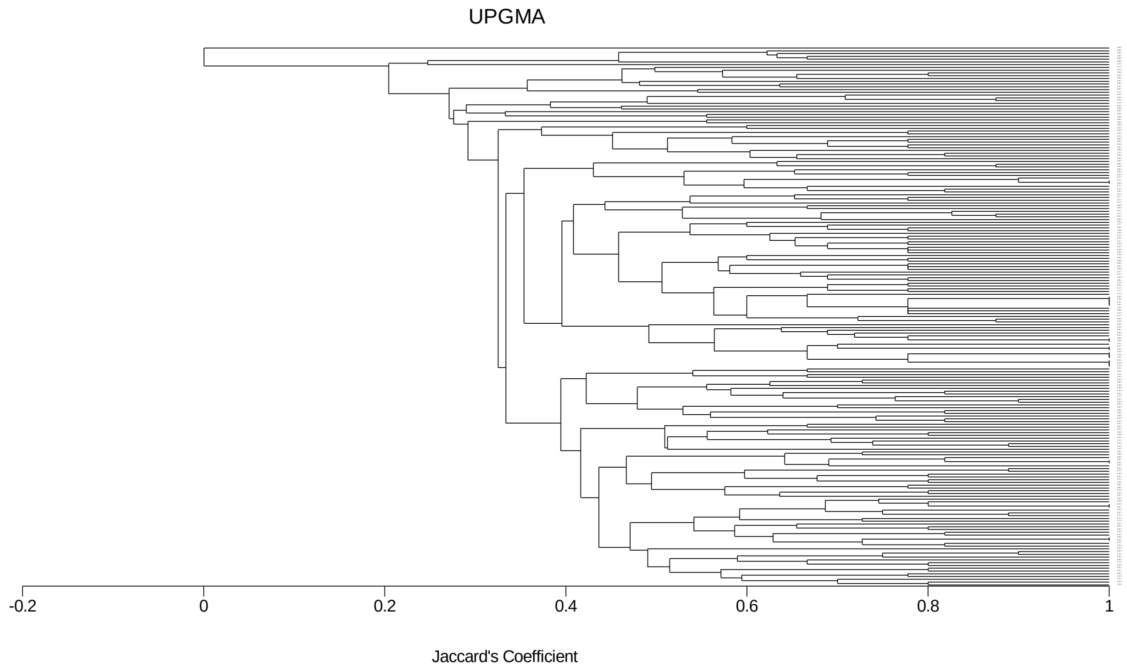



Figure 4.8: Dendogram showing the similarity between tilapia sites identified in Guangdong province, China

### 4.3.4 Bangladesh

#### 4.3.4.1 Prawn

According to literature prawn farming in Bangladesh has very little variation in the water management practices. This is reflected in the figure 4.8 where the groupings are shown at a very small distance. However using a Coefficient of 0.38, three groups were identified for further study in the project.

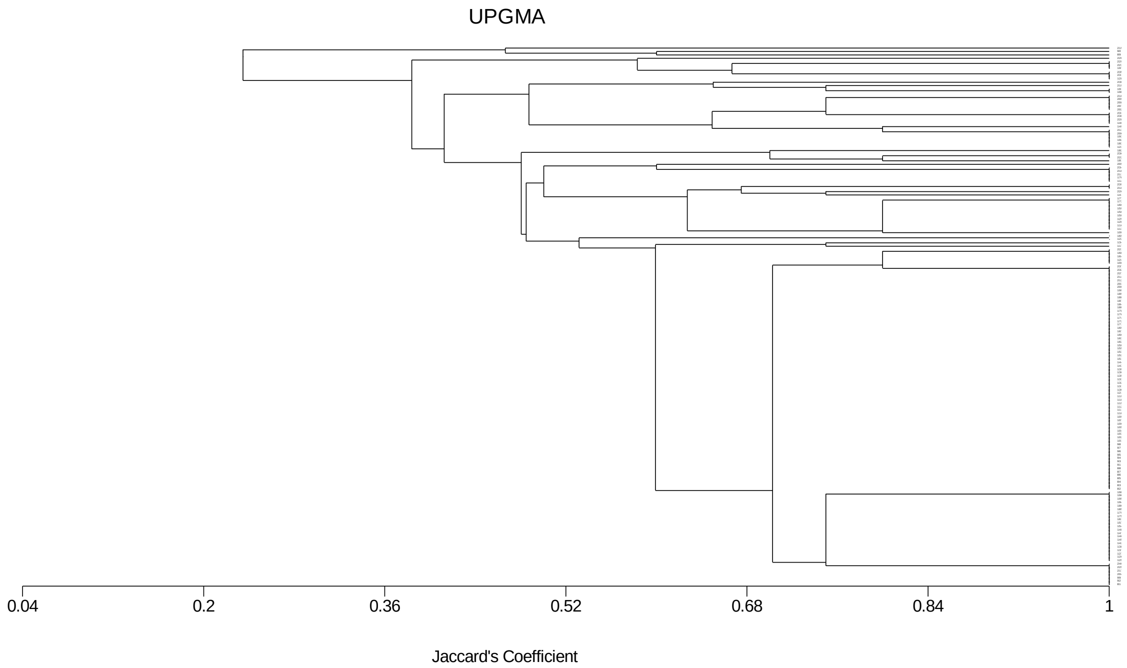



Figure 4.9: Dendogram showing the similarity between prawn sites identified in Bangladesh

#### 4.3.4.2 Shrimp

The groupings for shrimp reflected an initial 2 way split, which is again subdivided almost equally (figure 4.9). The two groups were used to provide the sites for further study in the SEAT project.

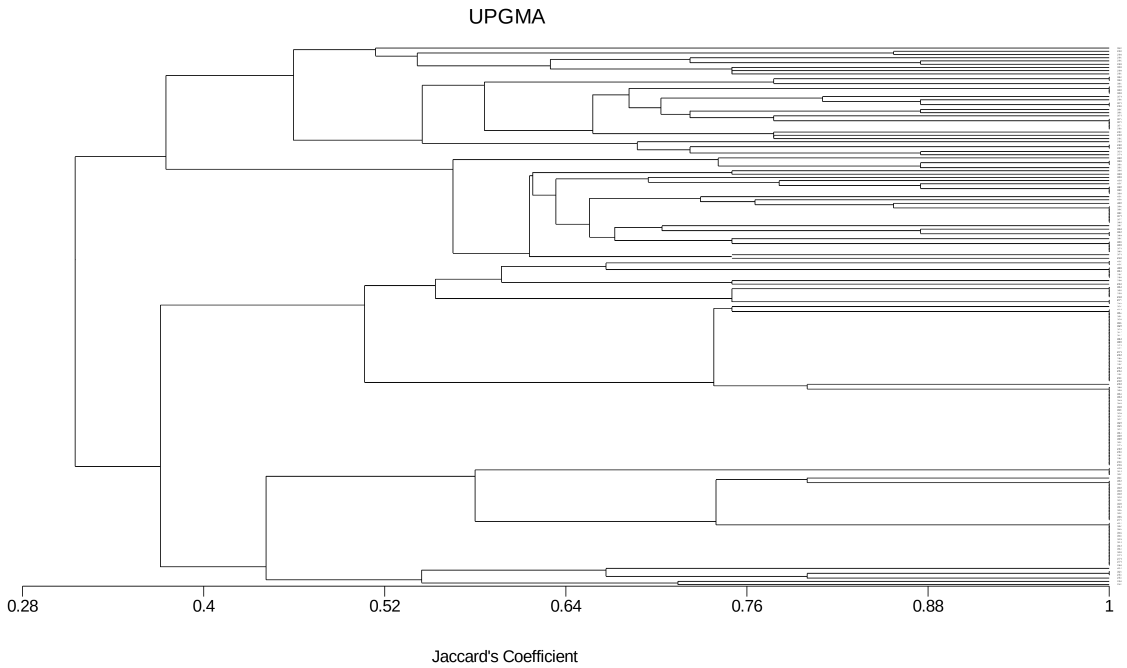



Figure 4.10: Dendogram showing the similarity between shrimp sites identified in Bangladesh

### 4.3.4.3 Polyculture

As with the prawn dendogram, the polyculture of shrimp and prawn (figure 4.10) shows an initial 2 groups but moving along the scale provides a better similarity coefficient and also a split into 3 groups. The farms within these groups were used as the basis for site selection and further analysis for the models.

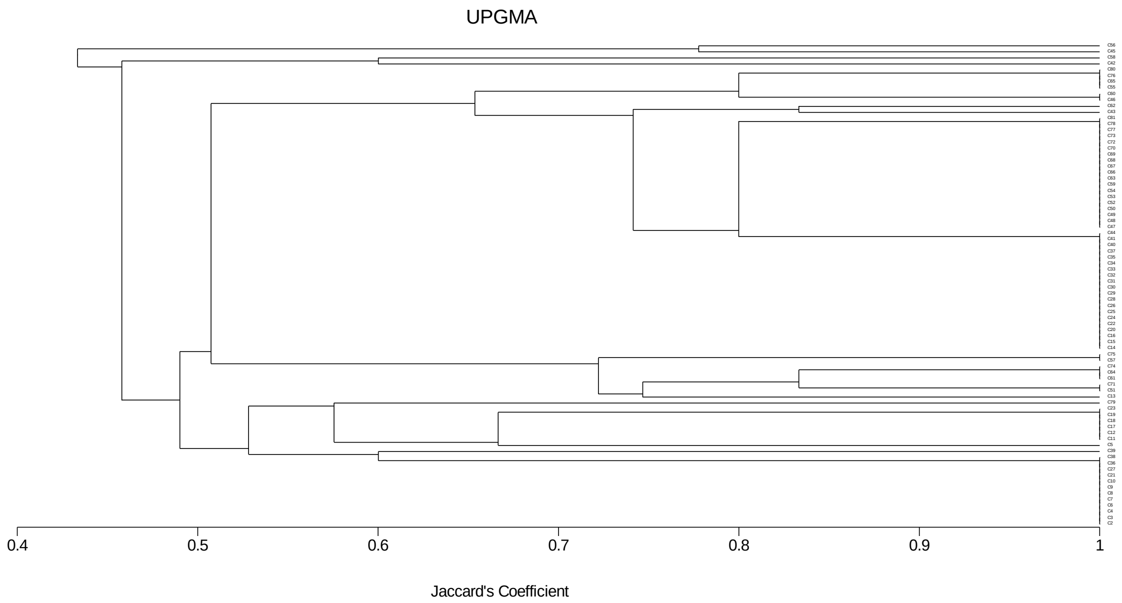



Figure 4.11: Dendogram showing the similarity between polyculture sites identified in Bangladesh

### 4.3.5 Groupings

The results from the correspondence analysis provided groups of farms which were used as sites for further, in depth study. Due to the number of farms, the selection was narrowed further to provide case studies for the models.

Randomisation of the groups in Excel provided the sites for further study in each country, resulting in farms from the major producing areas in each country (figure 4.11). Each farm selected from each group has some significant features highlighting the difference between the farm water management practices, the major differences are shown in table 1.

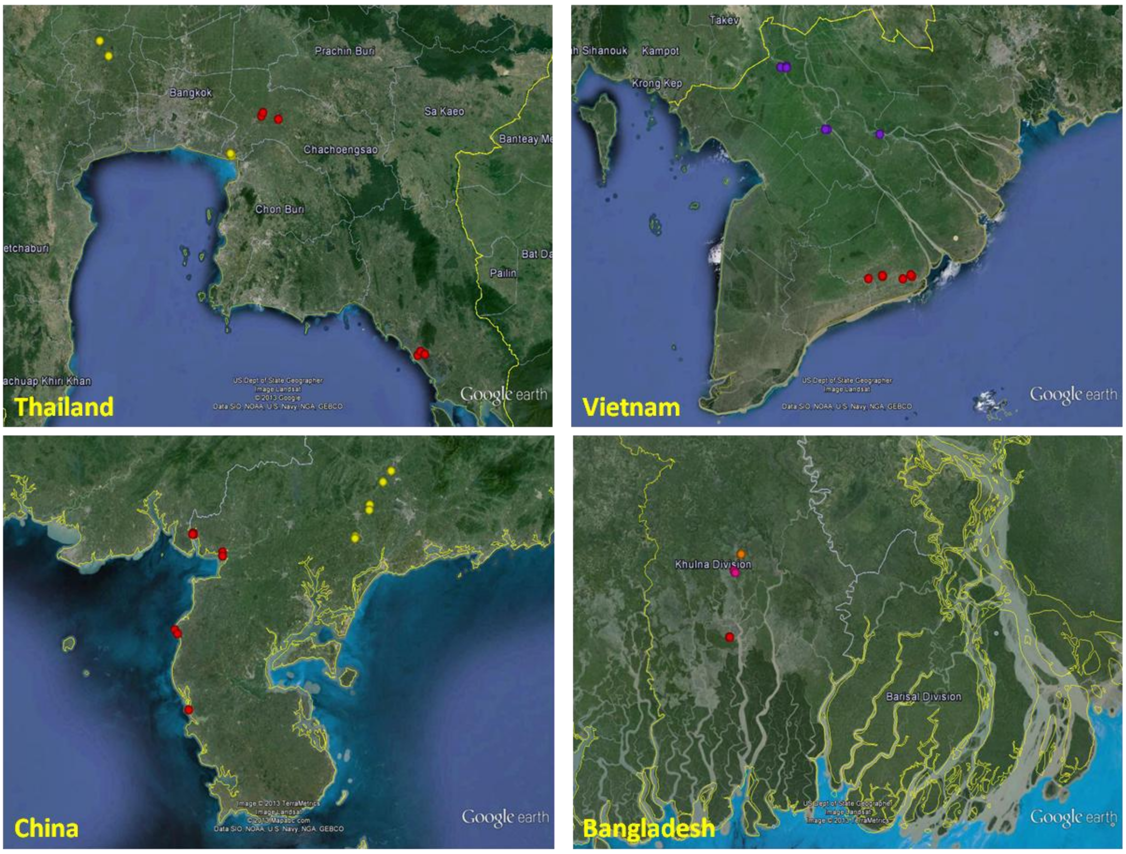



Figure 4.12: Location of sites selected for data collection (Yellow- tilapia, Red- Shrimp, Purple- pangasius, Orange- prawn, Pink- both; Bangladesh only)

The outcome indicates that shrimp farming employs similar water management practices regardless of location in Thailand, Vietnam and Bangladesh, which may be due to the rapid spread of shrimp farming that has occurred in recent years. China, however seems to have more farms which are spread over a number of groups showing a diversity of water management practices. This is possibly to do with modernisation as the fourth group appears to be sending its effluent to another place instead of returning directly to a coastal outfall like most of the other groups or the moving away from chemical treatments of the effluent as group 3 demonstrates in table 4.1. Tilapia farming water management practices show a similar trend to the shrimp results. There appears to be a general method in each country resulting in a large group clustered together on the dendogram for each country. In Thailand the major difference between the groups is based on whether or not recirculation is applied to the farms. However in china it appears to be based more on the water source and the treatment of any effluent (table 4.1).

As is well known pangasius culture varies little however water management practices provide an insight to any difference in the culture or the shift towards more sustainable methods of water management through the use of recirculation systems and storage ponds (table 4.1).

It is apparent that the use of Correspondence analysis provides an important insight into the water management practices within aquaculture systems. The results show that there is clearly much similarity within species but with an indication of the possible move towards diversification of water management.

**Table 4.1. Table showing the major factors defining the groups outlined in the cluster analysis.**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Thailand Shrimp farms** | | | | **Thailand Tilapia farms** | | |
| **Group 1** | **Group 2** | **Group 3** | | **Group 1** | **Group 2** | **Group 3** |
| Non Recirculating | Partially recirculating | Fully recirculating<br><br>Utilises storage ponds | | No recirculation<br>Water exchange at least twice per month | Utilises settlement ponds | Fully recirculating |
| **Vietnam Shrimp farms** | | | | **Vietnam pangasius farms** | | |
| **Group 1** | **Group 2** | **Group 3** | | **Group 1** | **Group 2** | **Group 3** |
| Partial drainage | No water exchange, water loss is topped up | Utilises storage ponds | | Source water from irrigation canal | | Fully recirculating<br>Treats water through settlement |
| **China Shrimp farms** | | | | **China tilapia farms** | | |
| **Group 1** | **Group 2** | **Group 3** | **Group 4** | **Group 1** | **Group 2** | **Group 3** |
| Water exchange occurs at least twice a month | Sediment is removed frequently, at least once a month | A second source of water is utilised | Effluent is released to a drainage canal not directly to the sea | Effluent is released to the river | Water is sourced from a lake | Sediment is deposited in nearby wasteland or woodland |

| | | | | |
|---|---|---|---|---|
| Effluent release to mangroves | | Water is not treated in anyway | Sediment is removed in frequently less than once per year. | Water is chemically treated<br>Drain out to a rice field |
| **Bangladesh farms** | | | | |
| **Shrimp** | **Prawn** | **Both** | | |
| Source water from the river | Source water from rainfall | Sediment deposited in own fields | | |
| Rely on rain for top up | Utilise pumped ground water to top up | | | |
| Water exchange | | | | |
| Sediment added to pond dyke | | | | |

## 4.4 Discussion

Site selection from large preset sites is an issue facing many groups in a multidisciplinary project. While reasoning may be provided for a large set of sites it is important for those requiring subsets of sites to carry out selection objectively and in a way that allows the sites to remain relevant to the selected area of research.

Multivariate analysis is used widely in biological science for the identification of similarities between data sets (Kent and Coker, 1992). It is an important tool due to its ability to handle large data sets. Ordination methods produce a graphical output allowing the user to easily visualise any signs of similarity within the applied data. The use of multivariate analysis in aquaculture has tended to be to define relationships between differing datasets with variations in the multivariate methods used.

Rahman *et al*. (2008) investigated the relationships of variables related to the food web in rohu (*Labeo rohita*) ponds, using direct gradient analysis. The method provided biplots relating to the effect of adding common carp (*Cyprinus carpio*) and feed on the water quality and fish growth in the system. Water quality is a popular topic for the application of multivariate analysis. A study by Nhan et al (2006) used three methods of multivariate analysis; Canonical correlation analysis, cluster analysis and discriminate analysis, to investigate the impact of feed input patterns on water and sediment quality. Other uses include the use of principal component analysis to investigating the effect of stocking density of caged Atlantic salmon welfare (Turnbull *et al.,* 2005) and the characterisation of shrimp farming systems in the Mekong delta in Vietnam by applying a cluster analysis on technical and economic data (Joffre and Bosma, 2009).

While the multivariate analysis is popular for biological interactions it is still to be more widely accepted in other sectors. The methods have not been widely adopted in the field of ecotoxicology, however Van den Brink *et al*. (2003) discusses the usefulness of various multivariate analysis methods for a range of ecotoxicological data sets. The author concludes that ordination methods may be of particular use but acknowledges that the complicated nature of some of the other methods require further communication from statisticians.

The methods used in this study are most commonly used for biological data, however this study does not compare the effects of one data set on another but examines the similarity of farms by using ordination methods on the water management practices. This is used to classify groups of farms using similar methods of water management to objectively select sites for further study in the SEAT project. This is a novel approach for aquaculture site selection, however has been previously applied to forest site selection (Burton *et al.,* 1991). The advantage to using the methods outlined in this chapter are that sites were selected relating to the research in an objective manner, removing the location bias in the original sites and allowed sites to be grouped and selected using water management practice data, which was considered most important for environmental modelling purposes.

# CHAPTER 5

# MODEL CASE STUDIES

## 5.1. Introduction

Aquaculture expansion in South East Asia has resulted in considerable deliberation of its effect on the environment and whether its continued expansion, if continuing as at present, is sustainable or not. It has been reported that aquaculture practices cause degradation of the environment and have resulted in destruction of mangroves and pollution of public water bodies (Black, 2001). Although aquaculture itself is not wholly responsible for this, it has resulted in negative media attention and therefore financial losses to the industry globally (Little *et al*., 2012). The management of aquaculture farms varies widely and through this variation, inevitably results in varying degrees of effluent quality. Although the quality of effluent is a major concern for the environment and other users, it is equally important to the farmer that the water quality is at a good standard to promote efficient and healthy growth of stock (Boyd and Tucker, 1998).

The culture of the 3 described species varies from extensive to intensive, however is predominantly either semi intensive or intensive in the case study countries.

Aquaculture farms require a certain level of water quality in order to maintain efficient growth of the production species. 3mg/l of DO is considered to be the lower limit for closed system pond culture by many groups in the aquaculture industry in SE Asia (FAO, 1978). Species subjected to low DO levels experience reduced feeding and therefore growth, in turn reducing the profitability of the farm (Allan and Maguire, 1991). It has been reported that pond farms discharge their water directly to water bodies (Lefevre *et al.,* 2011), so the high levels of nitrogen and phosphorus in farm effluent can lead to eutrophication and thus reduced DO levels in the source water of other and their own culture systems.

In relation to fish culture, tilapia and pangasius catfish are both considered to be largely tolerant to changes in water quality and are robust as a species, making them popular aquaculture subjects (Lefevre *et al.,* 2011; Atwood *et al.,* 2003). Tilapia is well known for its tolerance to temperature and salinity changes, and to low dissolved oxygen levels (El-Sayed, 2006), while pangasius, having the use of a facultative lung, has the ability to breathe air directly allowing the assumption that lower water quality may be more acceptable for this species (Browman and Kramer, 1985).

Tilapia as a species is tolerant to wide ranging changes in some environmental parameters. The Nile tilapia (*O. niloticus*) is the least tolerant of the tilapias, though is the most popular culture species in SE Asia (Mjoun et al., 2010). In accordance with the agreement that 3mg/l should be the lowest limit for good water quality in a pond, tilapia growth is at its most efficient at concentrations above this (Ross, 2000). Although early studies have shown them to survive in concentrations of 0.1mg/l (Magid and Babiker, 1975).

While tilapia have a tolerance to low DO, the catfish, *Pangasianodon hypothalamus* can survive even lower concentrations which would prove fatal to many other species as it is a facultative air breather (Lefevre et al., 2011; Browman and Kramer, 1985). Pangasius has been reported to survive in concentrations of 0.05 mg/l (Halls and Johns, 2013; FAO, 2010) for significant periods of time.

Penaied shrimp cultured in SE Asia and particularly in these countries has been adopted due to its popularity in foreign markets and its availability of seed from natural sources. Shrimp are particularly sensitive to degradation of water quality, however it has been shown that *Litopenaeus vannamei* are able to tolerate low salinity environments making them popular for polyculture systems with freshwater fish (Saoud and Davis, 2005).

A study by MacKay (1974) reported that *Penaeus schmitti* subjected to low levels of DO, 1.2mg/l, swam towards the surface in an attempt to gain access to higher DO levels, however in a short time they became immobile and began to die. The same study showed that if DO levels of 1.2ppm are introduced then around 50% of the shrimp may recover and survive. However, *P. monodon* is considered to be more resilient survived in DO levels of <1mg/l for short periods of time (Allan and Maguire, 1991; Liao and Huang, 1975).

## 5.2. Model case study sites and inputs

Case study farms were selected randomly from each classified group, as outlined in chapter 4. Results from the farmer survey (see Chapter 2) were used as the inputs for each case study and provided the inputs for the model as well as information on the management of the individual farms on practices such as water exchange and feed volumes and practices.  The results from feed analysis served as an indication of the changes of Total Nitrogen (TN) and Total Phosphorus (TP) in feeds applied to the system over the cycle (Chapter 2). Values for TN, TP and Dissolved Oxygen (DO) were analysed in the source water for each farm in the study as various points in the cycle (see Chapter 2 for methods). Variation in the sample numbers is a result of the level of permission to acquire samples from the system by farmers.

The models were adapted to account for the number of ponds on each farm in order to provide a more holistic view of the nutrient levels overall through the culture cycle. This is outlined in chapter 3 where the construction of the models is described.

Farms were given a unique code to allow anonymity and prevent any direct method of identifying farmers. The codes were composed of 2 letters followed by a number, identifying the Country followed by the aquaculture product. The number applies to the group outlined in Chapter 4 which the farm represents resulting in a farm ID i.e. **TS1** would represent a **T**hai farm producing **S**hrimp representing group **1.**

### 5.2.1. Thailand Shrimp

A farm from each group was selected as a representative for the farms within each group for further study, hereafter named farm 1, 2 and 3 after the group into which they were classified (see chapter 4). The farm layout for each is shown in figure 5.1. Thai shrimp farming occurs mostly in the region of Chachoengsao, Chon Buri, Surat Thani and Chantabui the farms selected as case studies are located in Chachoengsao and Chin Buri regions.  The owners of the 3 farms; TS1, TS2 and TS3, began farming in 1995, 1997 and 2001 respectively and have continued ever since. The main production factors affecting the model for each farm are shown in Table 5.1, however further chemical factors such as TN and TP levels in feed and water applied to the particular site were also incorporated in to the model. Rainfall data for each country was used to determine nutrient additions from this source also. From the illustrated differences in table 5.1 it should be noted that:

- pond size and water exchange vary between each farm,
- the largest size ponds are within medium sized farms (by pond number)
- the largest farm (by pond number), exchanges the most water throughout the cycle at 10% per week.

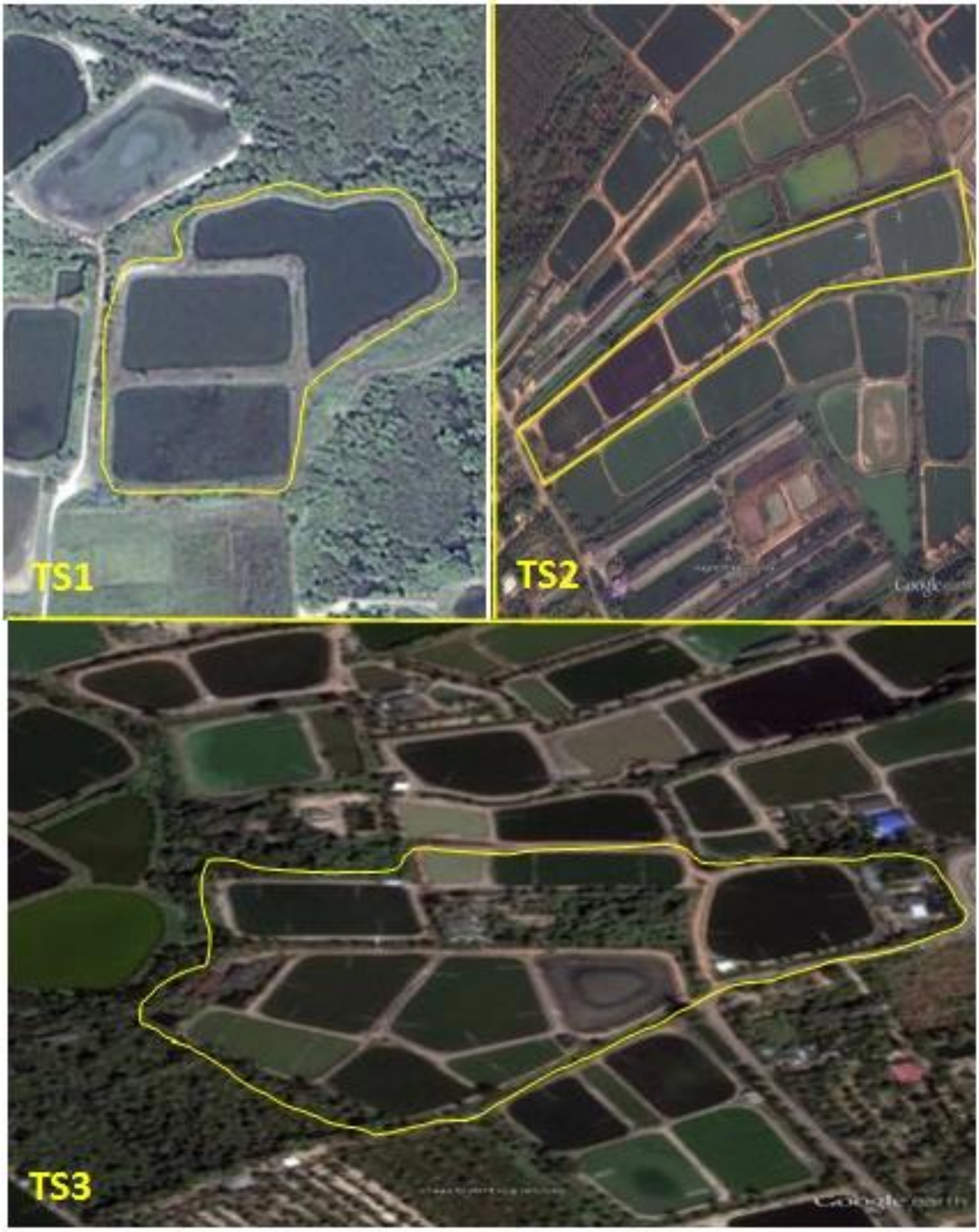



Figure 5.1: Layout of shrimp case study farms in Thailand. The yellow frames encompassing the ponds highlight the structure ad number of ponds in each farm ( GoogleEarth, 2013)

### 5.2.2. Thailand tilapia

Most of tilapia pond farming in Thailand is based in the regions of Suphan Buri, Nakhan Pathom, Phetchaburi and Chachoengsao, the farms selected for further study are located in the regions of Suphan Buri and Chachoengsao. The farms selected are known as TT 1, 2 and 3 based on their grouping from the MVA carried out in chapter 4. As previously mentioned tilapia farming in Thailand has been around since the 1960's, and case study sites TT2 and TT3 have been practicing aquaculture since 1970 and 2001 respectively. TT1 did not provide a start date for the farm. The farm layouts are shown in Figure 5.2, indicating the number of ponds located in the farm. Table 5.1 provides the main production factor variations in the model for the farms. As with the shrimp case studies chemical data for each farm was included in the model for feed, water and other additions such as rainfall.  The main points to consider are:

- farms with larger numbers of ponds have smaller size ponds, possibly due to the cost of land in the region.
- The larger the farm the higher the water exchange rate (by water area
- The farm with the highest rate of water exchange does not use aeration on its ponds.

Table 5.2 provides the data collected from each farm with regards to samples analysed. The source water results for TP, TN and DO were used as the initial inputs for the models and for water exchange throughout the cycle. Feed results were used to account for any changes in the feed TN and TP additions from feed over the course of the cycle.


Figure 5.2: Tilapia case study farms in Thailand. The yellow frames encompassing the ponds highlight the structure ad number of ponds in each farm (GoogleEarth, 2013)

## Table 5.1. Farm management for Thailand case studies

| Shrimp | Culture period days | Stocking density (individuals/ $m^2$) | Number of ponds | Average pond area ($m^2$) | Pond depth (m) | Total feed added (ton) | Average harvest size | Water exchange | Fertiliser | Aeration |
|---|---|---|---|---|---|---|---|---|---|---|
| TS 1 | 80 | 78 | 3 | 5568.46 | 2 | 30 | 11.76g | 30% every 2 weeks | Yes | Yes |
| TS 2 | 110 | 44 | 5 | 7263.97 | 2.5 | 45 | 22.22g | 5% every 2 weeks* | No | Yes |
| TS 3 | 100 | 46.88 | 8 | 2707.61 | 1.8 | 90 | 15.39g | 10% weekly* | Yes | Yes |

| Tilapia | Culture period days | Stocking density (Individuals/ $m^2$) | Number of ponds | Average pond area ($m^2$) | Pond depth (m) | Total feed added (ton) | Average harvest size | Water exchange | Fertiliser | Aeration |
|---|---|---|---|---|---|---|---|---|---|---|
| TT 1 | 210 | 9.4 | 1 | 5910.839 | 1.5 | 6 | 333g | 30% every 2 weeks | No | No |
| TT 2 | 180 | 0.625 | 3 | 5047.16 | 2 | 3 | 500g | 10% every 10 days* | No | Yes |
| TT 3 | 240 | 6.25 | 7 | 1803.83 | 1.5 | 5 | 650g | 10 every 2 weeks | No | Yes |

*These farms were Not Willing to Respond to questions based on water exchange therefore an average of the farms in the classified group was used.

**Table 5.2: Sample results collected from case study farms for Thai shrimp (TS) and tilapia (TT). (blank cells mark points where access to farm was denied by the farmer; H indicates where the ponds have been harvested)**

| Shrimp Farms | TS1 | | | | TS2 | | | | TS3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample number | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| DO in source water (mg/l) | 3.4 | - | 2.3 | 3.5 | 6.8 | 11.9 | 4.9 | 3.8 | 6.5 | 3.2 | 13.1 | 9.1 |
| DO in pond water (mg/l) | 6.7 | 5.7 | 4.6 | Harvested | 10.7 | - | 5.9 | 10.4 | 12.7 | 6.1 | 8.2 | - |
| TN in source water (mg/l) | 1.78 | - | 1.37 | 2.27 | 3.91 | 5.65 | 5.31 | 1.14 | 1.18 | 3.48 | 3.66 | 3.38 |
| TN in pond water (mg/l) | 0.69 | 2.07 | 7.14 | Harvested | 4.63 | 3.84 | 10.9 | 6.48 | 2.07 | 7.34 | 11.8 | 4.15 |
| TP in source water (mg/l) | 0.05 | - | 0.06 | 0.07 | 0.36 | 1.44 | 0.16 | 0.38 | 0.08 | 0.29 | 0.06 | 0.07 |
| TP in pond water (mg/l) | 0.05 | 0.05 | 0.37 | Harvested | 0.26 | 0.17 | 0.15 | 0.41 | 0.12 | 0.41 | 1.07 | 0.12 |
| TN in feed (%) | 6.93 | 6.26 | 7.06 | - | 4.84 | 6.58 | 6.76 | 11.07 | 5.93 | 5.75 | 6.40 | 6.52 |
| TP in Feed (%) | 1.41 | 1.33 | 0.06 | - | 0.92 | 0.81 | 1.39 | 0.02 | 1.28 | 0.96 | 0.02 | 0.85 |
| TN in sediment (%) | - | - | -0.24 | - | - | - | - | -0.15 | - | - | -0.19 | - |
| TP in sediment (%) | - | - | 2.22 | - | - | - | - | 2.52 | 0.08 | - | 2.24 | - |

**Table 5.2 Cont.**

| Tilapia Farms | TT1 | | | | TT2 | | | | TT3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample time | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| DO in source water (mg/l) | 5.2 | 1.4 | 6.1 | 3.4 | 5.4 | 1.5 | 10.6 | 9.4 | 7.4 | 9 | 2.9 | 0.9 |
| DO in pond water (mg/l) | 4.9 | 4.7 | 6.5 | 6.4 | 7.4 | 12.2 | - | - | 8.4 | 15.2 | 3.2 | 6.5 |
| TN in source water (mg/l) | 3 | 4.16 | 6.68 | 3.4 | 2.34 | 1.25 | 6.32 | 2.76 | 3.04 | 4.48 | 3.31 | 3.08 |
| TN in pond water (mg/l) | 3.43 | 4.75 | 8.29 | 6.27 | 1.62 | 1.5 | - | - | 3.47 | 7.89 | 5.94 | 7.97 |
| TP in source water (mg/l) | 0.99 | 0.81 | 0.74 | 1.6 | 0.13 | 0.38 | 1.19 | 0.11 | 0.34 | 0.27 | 0.25 | 0.56 |
| TP in pond water (mg/l) | 1.32 | 1.64 | 1.03 | 1.5 | 0.03 | 0.1 | - | - | 0.12 | 0.64 | 1.16 | 3.1 |
| TN in feed (%) | 2.80 | 7.23 | 2.71 | 3.88 | 3.49 | 4.72 | - | 4.23 | 7.29 | 4.19 | - | 2.69 |
| TP in Feed (%) | 0.83 | 0.03 | 0.89 | 1.24 | 1.16 | 0.06 | - | 1.48 | 0.01 | 0.99 | - | 1.40 |
| TN in sediment (%) | 1.26 | 0.10 | 0.13 | 0.12 | 1.24 | -0.17 | - | 0.17 | 0.32 | 0.13 | - | - |
| TP in sediment (%) | 0.04 | 2.86 | 0.08 | 0.10 | 0.01 | 3.09 | - | 0.05 | 1.37 | 0.05 | - | - |

### 5.2.3. Vietnam shrimp case studies

The main areas for Penaeid shrimp farming are in 3 provinces in the Mekong Delta; Soc Trang, Bac Lieu and Ca Mau. The case study farms are located in Soc Trang and their layouts are shown in Figure 5.3. The images show the variation in the number of ponds, with the farm structure outlined in yellow. . Unlike shrimp farms in Thailand, the case studies for Vietnam indicate that the larger farm, VS2, also has the larger average pond size, whereas the smallest farm, VS3, has the smallest average size pond. Table 5.3 indicates the variations in the farm production factors, including any additions to the system such as total feed, fertilisers and the use of aerators. Data for TN, TP and DO levels in feed and water were also included in the model to provide a better reflection of the system inputs. Rainfall for the Mekong Delta was also included to determine if there are significant additions from this source of TN and TP. Table 5.4 provides the data collected from each farm with regards to samples analysed. The source water results for TP, TN and DO were used as the initial inputs for the models and for water exchange throughout the cycle. Feed results were used to account for any changes in the feed TN and TP additions from feed over the course of the cycle.


Figure 5.3. Images of the layout of the case study farms for Vietnamese shrimp. The yellow frames encompassing the ponds highlight the structure ad number of ponds in each farm (GoogleEarth, 2013)

### 5.2.4. Vietnam pangasiid catfish case studies

The pangasius sector is located in the Mekong Delta and spans 3 provinces, An Giang, Can Tho and Vinh Long. The case study farms are found in the provinces of An Giang and Can Tho. The three case study farms (VC1, 2 and 3) have been in business since 1995, 1990 and 2004, respectively. The layouts of the farms for the case study are found in Figure 5.4, which shows no significant change in number of ponds in the farm however there are still shown to be smaller size ponds in the farm with a greater number of ponds (VC1). The recorded water exchange at each farm was found to vary between 30 and 70% and occurs daily. However it should be noted that VC1 applies aeration to the ponds, which is an unusual activity in pangasius farming (Lefevre et al, 2011) and may help towards improving the water quality being released to the environment (table 5.2).

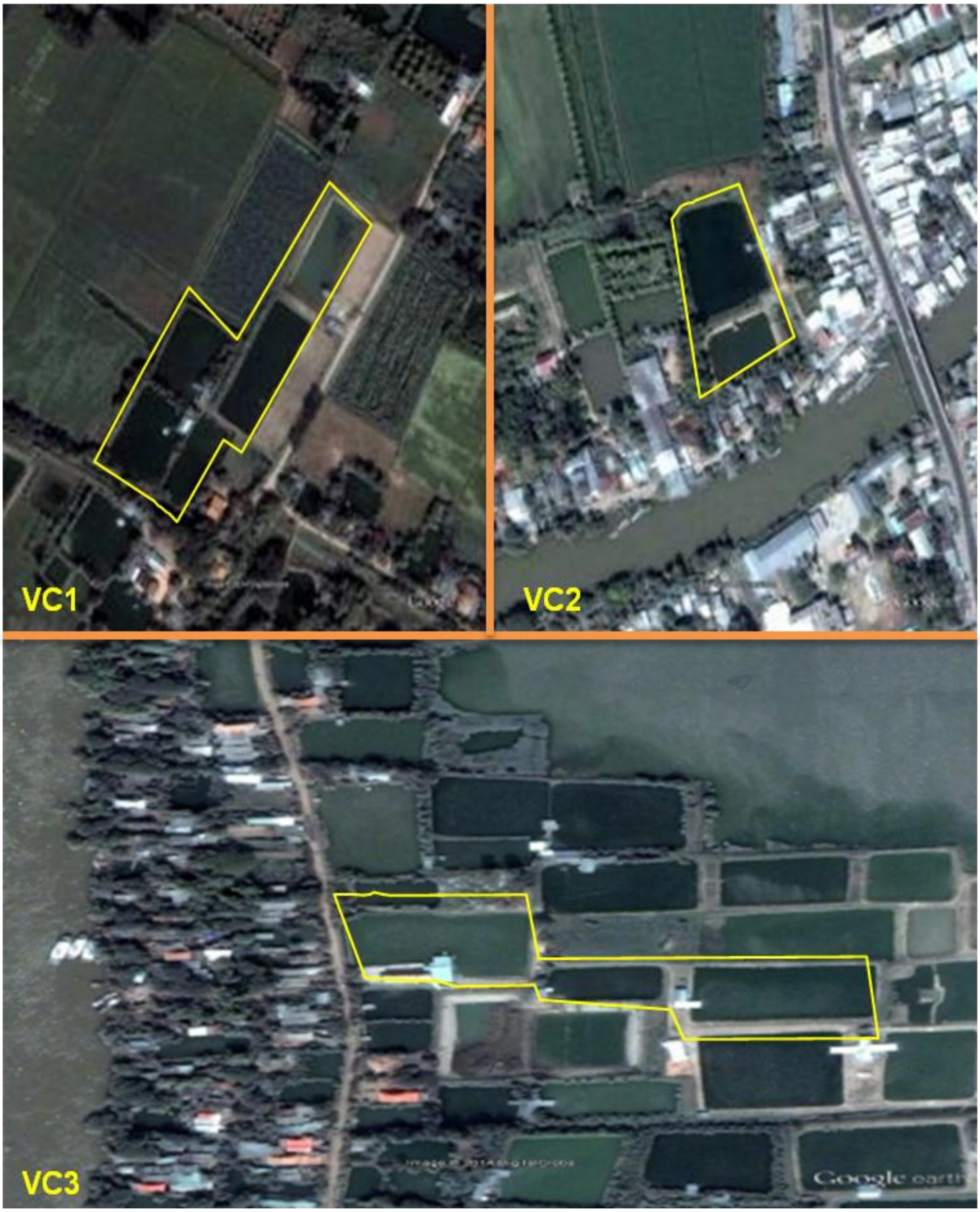



Figure 5.4. Images of the case study catfish farms in Vietnam. The yellow frames encompassing the ponds highlight the structure ad number of ponds in each farm (GoogleEarth, 2013)

## Table 5.3: Farm management for Vietnamese case studies

| Penaeid Shrimp | Culture period (days) | Stocking density (Individuals/ $m^2$) | Number of ponds | Average pond area ($m^2$) | Pond depth (m) | Total feed added (tons) | Average harvest size (g) | Water exchange | fertilisers | Aeration |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 135 | 35 | 16 | 4342.19 | 1.7 | 30.37 | 26.32 | 15% every 2 weeks | Yes | Yes |
| 2 | 150 | 42 | 41 | 5121.99 | 2.2 | 108.23 | 26.32 | 15% every 2 weeks | Yes | Yes |
| 3 | 120 | 18 | 5 | 2480.91 | 1.5 | 6.5 | 25 | 20% daily | Yes | Yes |

| Pangasiid Catfish | Culture period (days) | Stocking Density (individuals/ $m^2$) | Number of ponds | Average pond area ($m^2$) | Pond Depth (m) | Total feed added (tons) | Average harvest size (g) | Water Exchange | Fertiliser | Aeration |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 200 | 20 | 5 | 1607.04 | 3.5 | 50 | 1500 | 55% daily | No | Yes |
| 2 | 210 | 46 | 2 | 2179.98 | 2 | 257.35 | 950 | 70% daily | No | No |
| 3 | 150 | 30 | 3 | 2698.51 | 5 | 150 | 1200 | 30% daily | No | No |

**Table 5.4: Sample results collected from case study farms for Vietnamese Shrimp (VS) and catfish (VC).**

| Farm | VS1 | | VS2 | | VS3 | |
|---|---|---|---|---|---|---|
| Sample time | 1 | 2 | 1 | 2 | 1 | 2 |
| DO in source water (mg/l) | 4.98 | 5.83 | 5.15 | 6.47 | 4.88 | 5.11 |
| DO in pond water (mg/l) | 4.75 | 4.11 | 5.16 | 4.78 | 11.82 | 4.22 |
| TN in source water (mg/l) | 0.397 | 0.666 | 0.811 | 0.863 | 0.9 | 1.231 |
| TN in pond water (mg/l) | 0.591 | 1.072 | 0.654 | 2.014 | 1.972 | 2.643 |
| TP in source water (mg/l) | 0.0069 | 0.125 | 0.065 | 0.312 | 0.076 | 0.115 |
| TP in pond water (mg/l) | 0.12 | 0.219 | 0.106 | 0.26 | 0.109 | 0.199 |
| TN in feed (%) | 6.93 | 5.92 | 6.54 | 5.79 | 6.78 | 6.74 |
| TP in Feed (mg/g) | 2.52 | 2.84 | 3.08 | 2.86 | 2.78 | 3.01 |
| TN in sediment (%) | 0.548 | 1.046 | 0.57 | 1.105 | 0.212 | 0.698 |
| TP in sediment (mg/g) | 0.471 | 0.484 | 0.519 | 0.723 | 0.509 | 0.592 |

| Farm | VC1 | | VC2 | | VC3 | |
|---|---|---|---|---|---|---|
| Sample time | 1 | 2 | 1 | 2 | 1 | 2 |
| DO in source water (mg/l) | 2.47 | 6.2 | 1.9 | 2.4 | 4.15 | 6 |
| DO in pond water (mg/l) | 1.61 | 2.8 | 2.25 | 4 | 7.15 | 2.9 |
| TN in source water (mg/l) | 1.767 | 2.38 | 1.187 | 2.181 | 1.68 | 1.35 |
| TN in pond water (mg/l) | 18.392 | 7.37 | 3.581 | 5.18 | 3.67 | 6.27 |
| TP in source water (mg/l) | 0.358 | 0.163 | 0.772 | 0.783 | 0.155 | 0.94 |
| TP in pond water (mg/l) | 9.534 | 0.639 | 0.71 | 1.811 | 1.35 | 0.499 |
| TN in feed (%) | 3.04 | 4.82 | 4.11 | 3.02 | 3.45 | 4.58 |
| TP in Feed (mg/g) | 3.45 | 2.64 | 2.89 | 3.63 | 3.66 | 2.83 |
| TN in sediment (%) | 0.541 | 3.39 | 0.157 | 4.017 | 0.344 | 1.521 |
| TP in sediment (mg/g) | 0.224 | 0.936 | 0.335 | 0.85 | 0.171 | 0.218 |

## 5.3 Model Outputs

### 5.3.1. Thailand shrimp case study model outputs

#### 5.3.1.1. Total production

The model contains an output for production in each pond in the farms. Fig 5.5 shows TS1 containing 3 ponds producing a total of 12.08 tonnes, with a minimum of 3.65 tonnes and a maximum of 4.67 tonnes in a pond. TS2 (fig 5.5) produces 13.52 tonnes of shrimp over 5 ponds, averaging 2.7 tonnes per pond. Figure 5.5 Represents farm TS3. This farm has 8 ponds in total with a minimum production of 1.46 tonnes and a maximum of 2.55 tonnes and an output of 15.11 combined. Although TS3 is shown to be the larger farm with more ponds it is approximately the same weight of shrimp per pond as TS2.

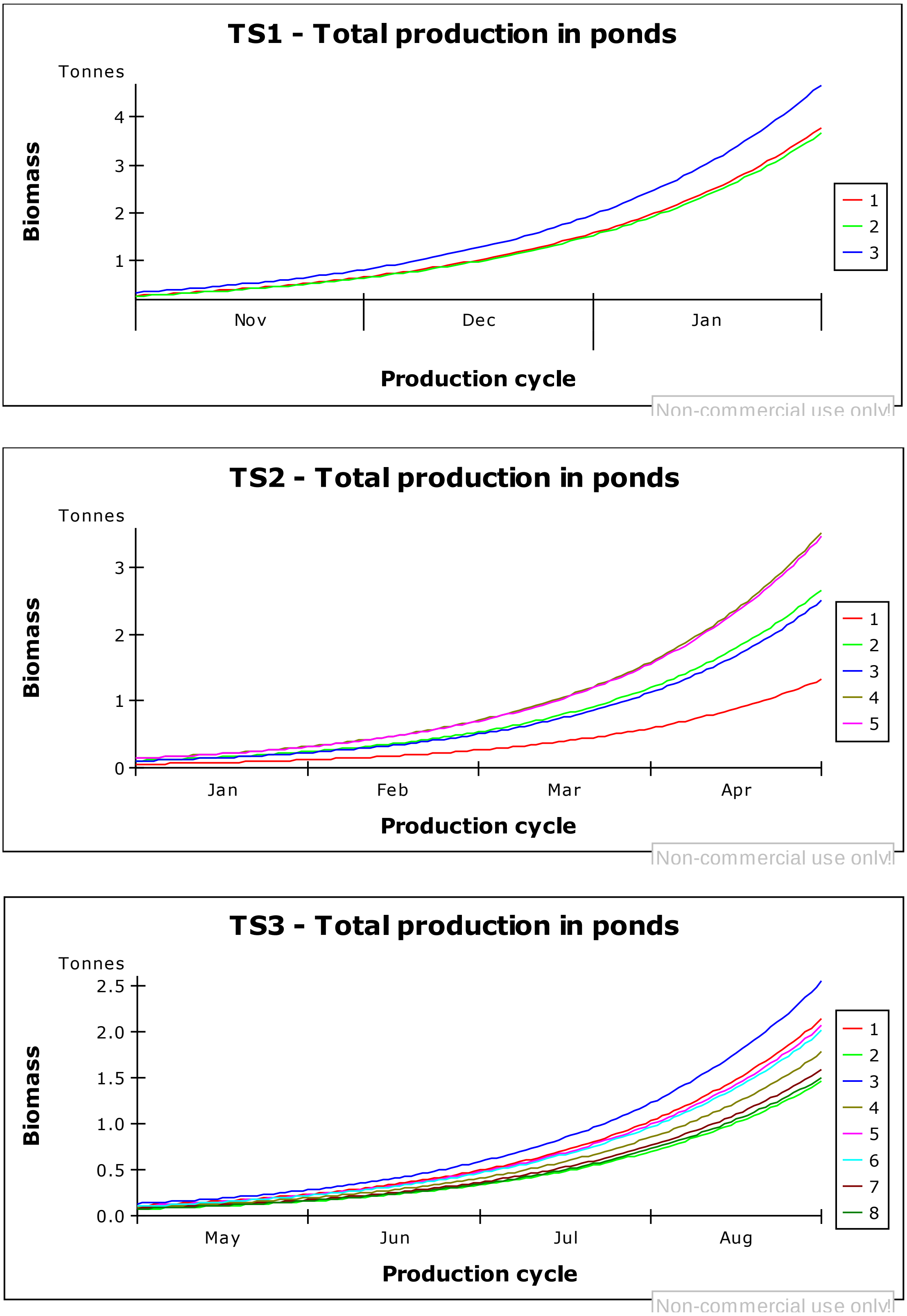
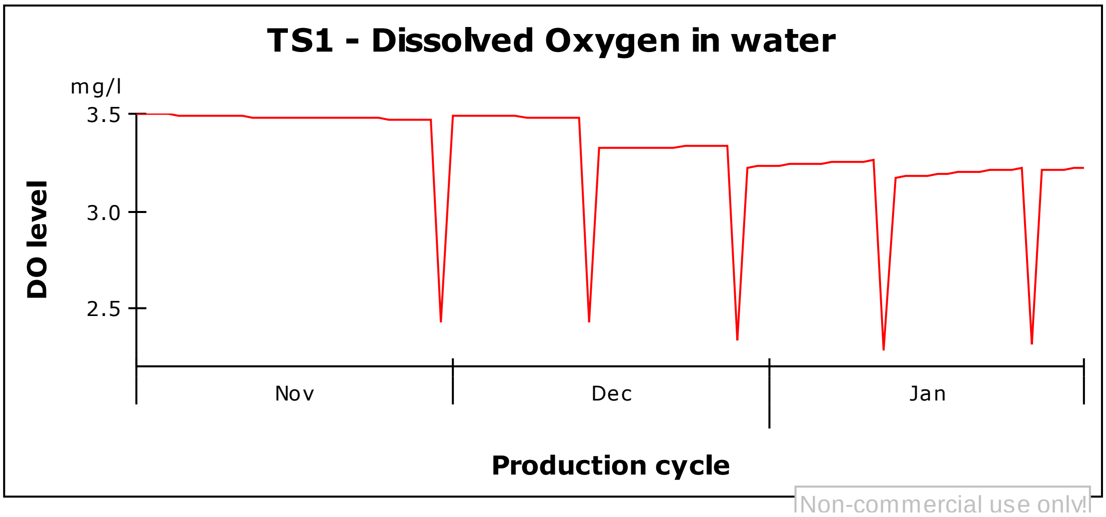
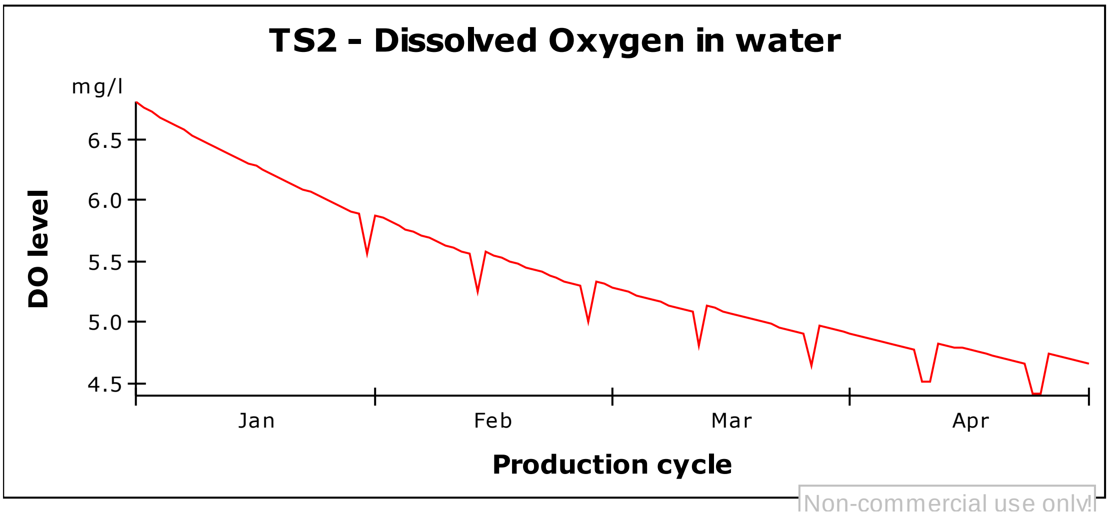



Figure 5.5: Total modelled production in three case study farms for Thai shrimp over a production period (TS1- 3 ponds; TS2- 5 ponds: TS3- 8 ponds) (PowersimTM output)

#### 5.3.1.2 Dissolved Oxygen

Dissolved oxygen is a major factor in water quality and has particularly damaging effects on both aquaculture stock and the surrounding environment if allowed to drop too low. Figure 5.6 represents the overall DO level within the farm and shows that there is an overall decrease in modelled DO levels over the course of a cycle in shrimp production. However the degree to which the level reduces to is highly important in investigating the water quality of the farm. TS1 shows the lowest drop in modelled DO over the course of the cycle form 3.5mg/l to 3.22mg/l. The pond modelled DO level drops by 1.08 mg/l during water exchange as the top layer of water is flushed out leaving the less oxygenated water, this however is replaced the same day with supply water with a recorded DO of 3.5mg/l. TS2 shows an overall drop in DO of 2.69mg/l from 6.85 mg/l to 4.16mg/l. 1mg/l are lost in the first month before water exchange, which reduces the DO by an additional 0.33mg/l, though is replaced the same day. TS3 has the largest reduction of DO over the cycle (3.12mg/l) from 8.15 to 5.03mg/l, however is shown to stay above 5mg/l.



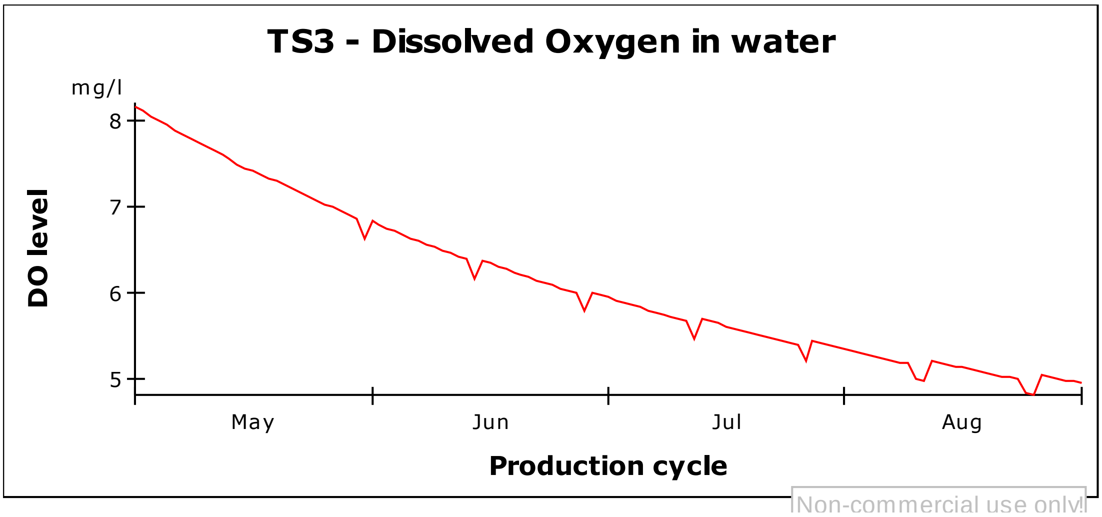
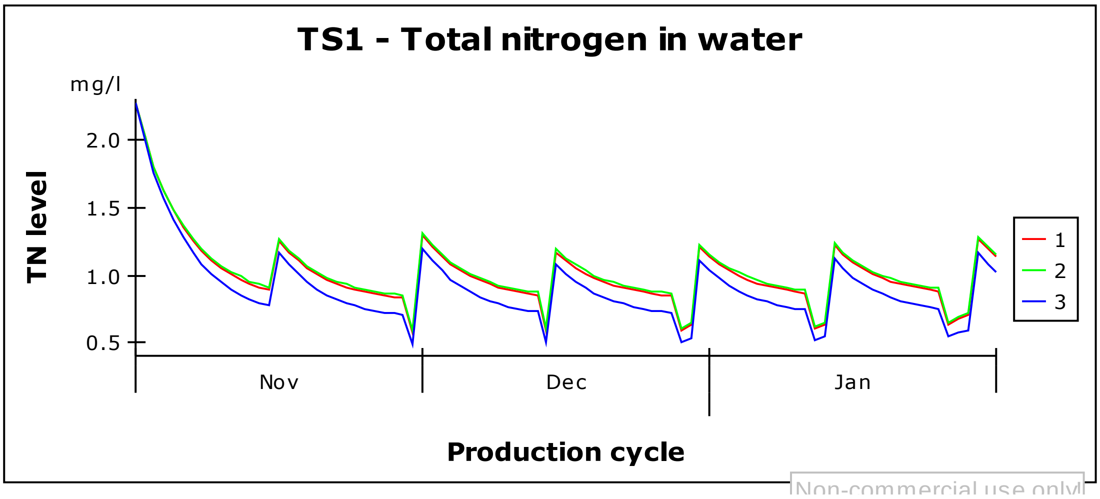
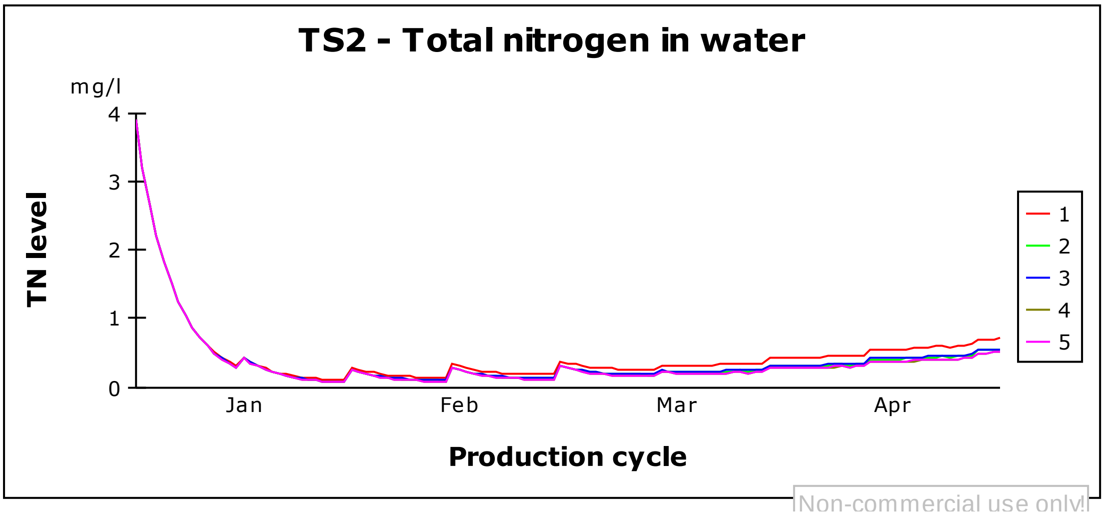




Figure 5.6: Model outputs for DO levels in pond water for shrimp ponds used in Thailand case study farms during the culture period (PowersimTM outputs)

#### 5.3.1.3 Total Nitrogen in water

Nitrogen is an important factor when considering the pollution potential of activities in aquatic systems (Chislock *et al*., 2013). It is especially important to monitor levels of total nitrogen in closed system aquaculture as there is the possibility of a build up of the nutrient resulting in the formation of toxic algal blooms in the production system (Alonso-Rodriguez and Paez- Osuna, 2003). The results from the model (figure 5.7) show an initial drop off of total nitrogen in the water, possibly due to the initial breakdown activities coupled with the first water exchange event. TS1 and TS2 farms show a reduction in the modelled TN level between flushing indicating that there is a higher level of TN in the supply water than in the pond water over the course of the cycle. Farm TS3 shows an increase in TN levels throughout the cycle, increasing from an initial level of 3.57 mg/l for each pond, increasing to an average of 4.08 mg/l with a minimum of 3.91 mg/l and a maximum of 4.22 mg/l. All farms exchange water at approximately 2 week intervals, shown in figure 5.6 by a decrease in modelled TN levels followed by an instant increase in TN around the event. TS1 and TS2 indicate that although there is the decline in the level between the water exchange events there is still an increase over the course of the cycle, albeit a small one. Farm TS3 shows an increase in modelled TN levels from the start of the cycle to the end, with an initial decrease during the first 2 weeks. It is possible that the water exchange activities are helping to keep the TN levels relatively low although the supply water contains more of the nutrient. TS2 shows an increase in TN levels at the end of February to the end of the cycle. This is possibly due to the change in the TN level found in feed increasing from 6.5% to 11.07%.



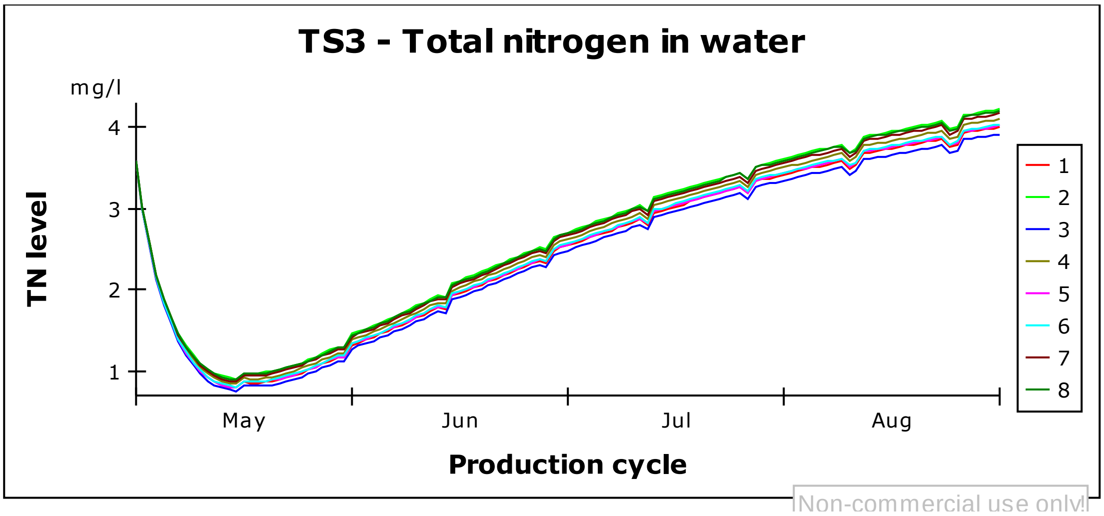
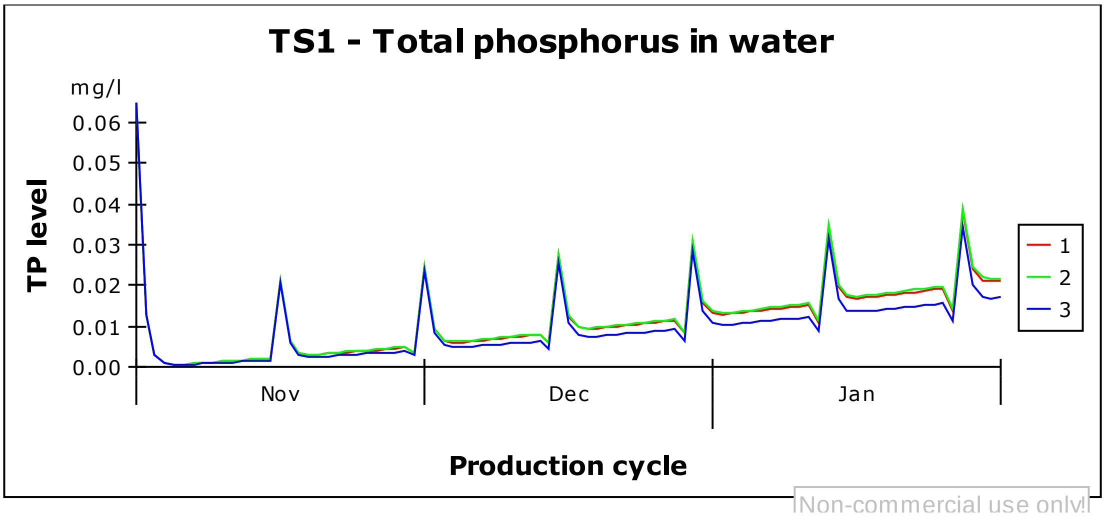



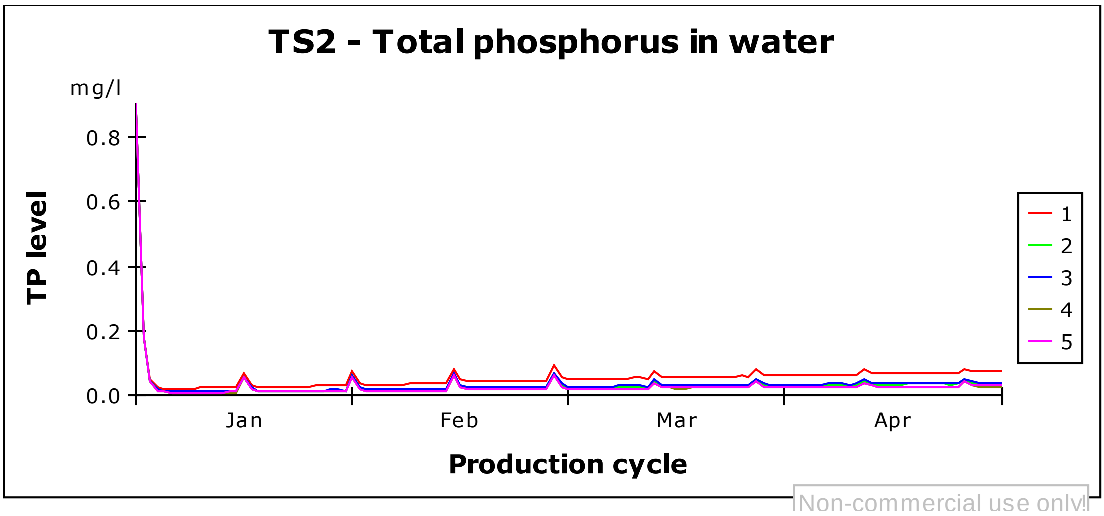

Figure 5.7. Model outputs for each Thai shrimp farm representing the total nitrogen in the water of each pond (PowersimTM output)

#### 5.3.1.4 Total Phosphorus in water

Figure 5.8 shows the modelled levels of TP in the farm water, with outputs tailored to each pond in the farm. Farms TS1 and TS2 show an increase in modelled TP levels in the water during water exchange activities.. The level of TP in TS1 shows an initial decrease, however increases over the course of the cycle as a whole. The final modelled TP level is an average of 0.02 mg/l for the farm with a minimum of 0.017 mg/l and a maximum of 0.022 mg/l.. The Powersim outputs for TS2 show an increase in the TP in the water, however in the first few days there is a drop from 0.91 mg/l to 0.0

1 mg/l. As previously mentioned the modelled level of TP shows an increase at the point of water exchange of 0.05 mg/l. (GAA, 2013). TS3 shows an overall increase in the modelled TP level in the ponds. The first five days see an increase from 0.12 mg/l to 0.3 mg/l. The overall increase from this point to the end of the culture cycle is 0.08 mg/l.



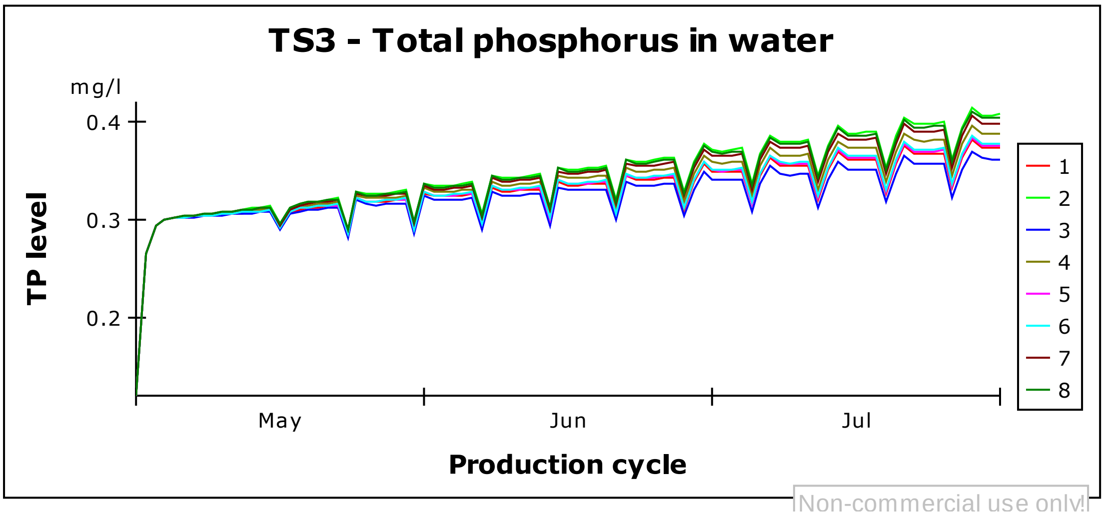




Figure 5.8. Model outputs for TP levels in each pond in the Thai shrimp farms (Powersim™ output)

#### 5.3.1.5 Total Nitrogen in sediment

Total nitrogen added to the sediment was modelled as the total for the farm as a whole to understand the level of accumulation in this sink for the three case study farms (fig. 5.9). Modelled total nitrogen added to the sediment, for farm TS1 was a 771.29 kg N. The model shows a small increase in the first month of TN loading followed by a steeper increase between month 2 and 3. Farm TS2 shows the largest modelled addition of TN to the sediment at 1387.71 kg N, though shows a similar trend to TS1.This is the largest farm by water area. Farm TS3 returns the lowest result of the 3 with a modelled TN addition of 137.09 kg. This observes a different trend to the first to case studies. A steep increase can be seen in the first two months of the cycle, reaching a peak of 181.21 kg TN. This is followed by a short decline of 42.12 kg TN. This farm is the smallest by water area, of the three. It applies the largest amount of feed and also applies fertiliser. The three results can be converted into additions of TN per $m^2$ by dividing the additions by the water area in the farm. This resulted in the modelled results showing an input of 138.5 g TN/m2 for TS1, 191 g TN/$m^2$ for TS2 and 50.6 g TN/$m^2$ for TS3. The modelled results suggest that water exchange has a large effect on the addition of TN to sediment as farm TS3 has the largest amount of feed added to the system, while also adding fertilisers but returns the least coverage inputs per $m^2$ of TN in the sediment, even though it is the smallest farm by water area (table 5.1).

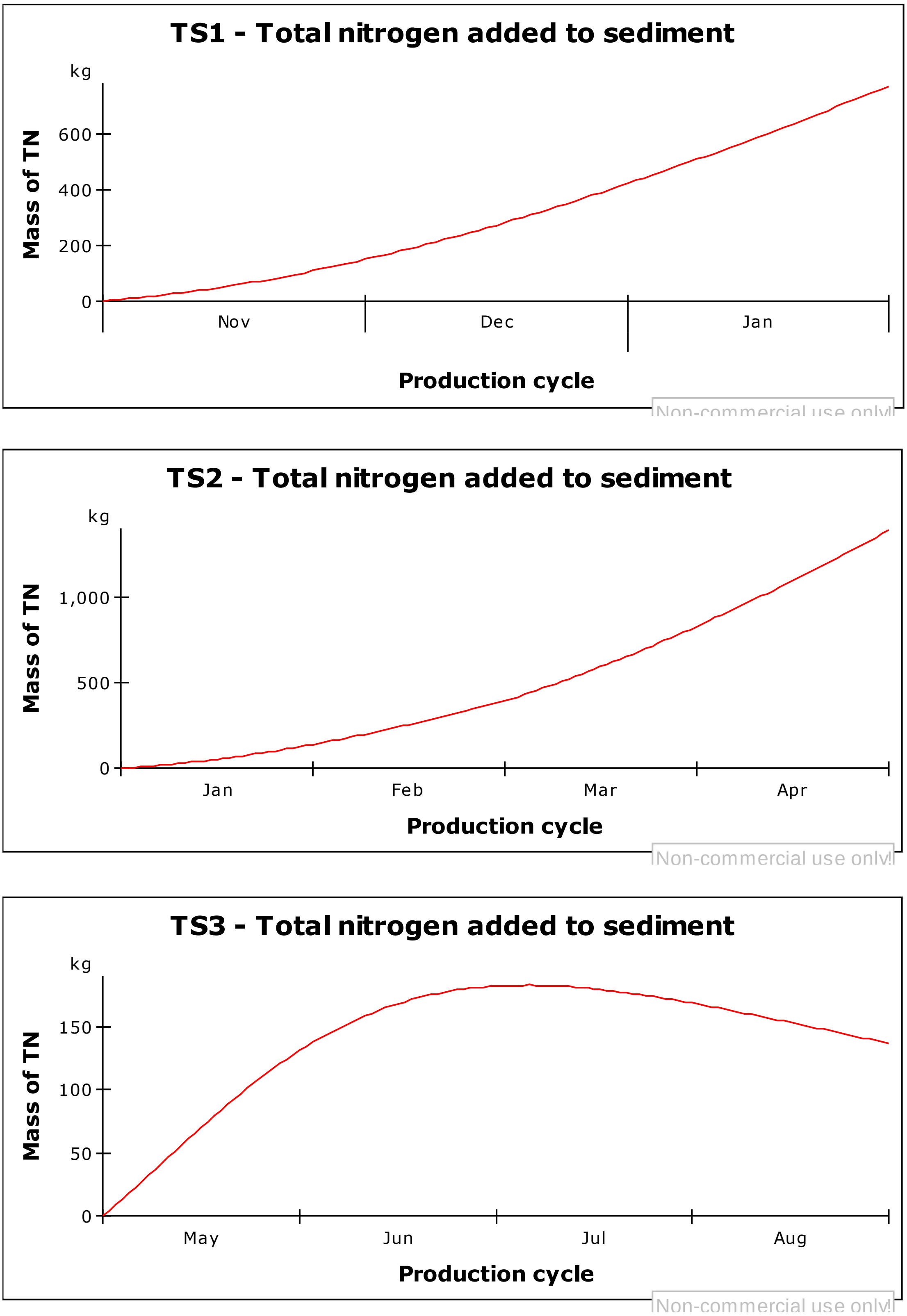
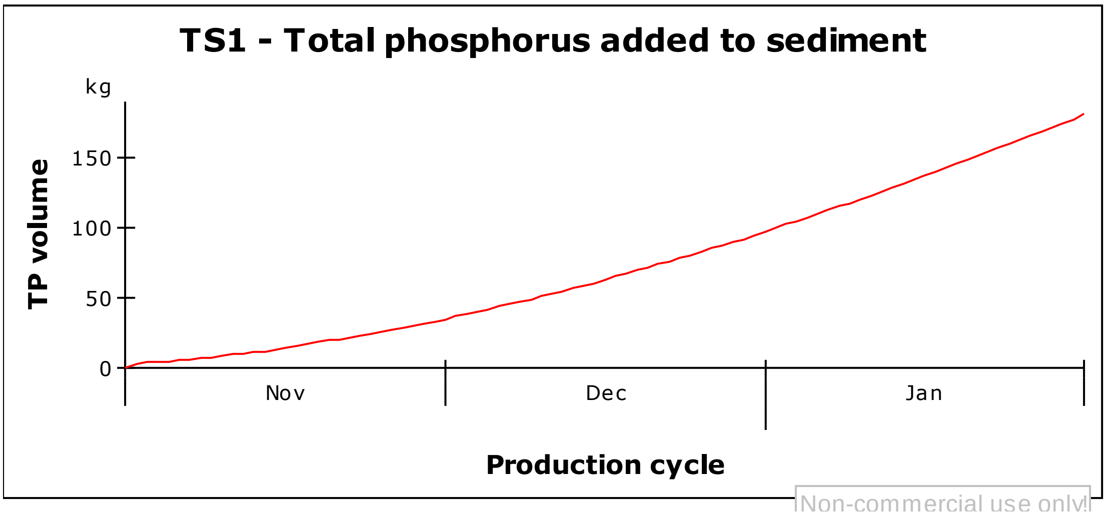
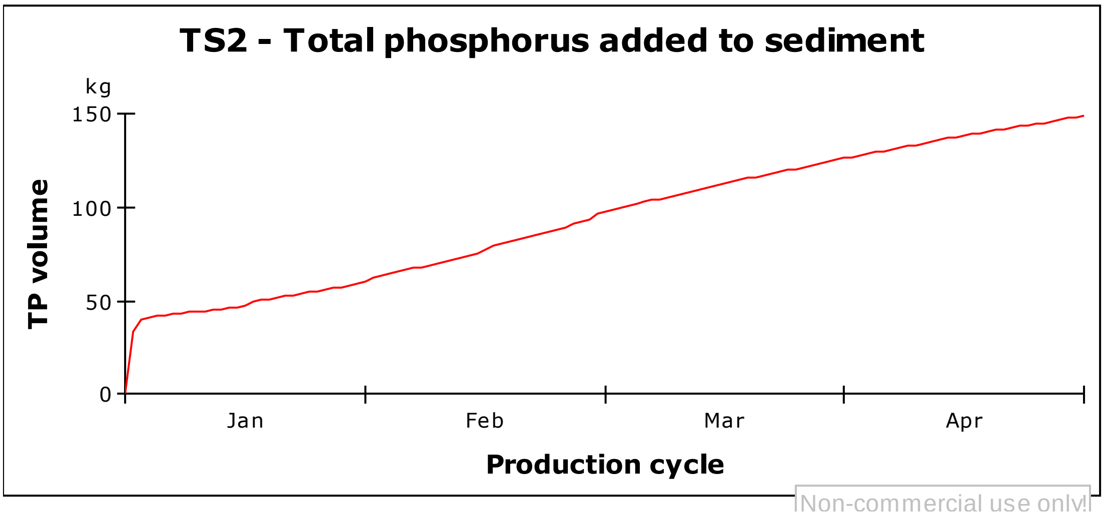



Figure 5.9: Model outputs for TN added to sediments for Thailand case study farms during the culture period (Powersim$^{TM}$ outputs)

#### 5.3.1.6 Total Phosphorus in sediment

As with the total nitrogen to sediment model, total phosphorus added to the sediment was modelled as the total for the farm as a whole to understand the level of accumulation in this sink for the three case study farms (fig. 5.10). Modelled total phosphorus added to the sediment, for farm TS1 was 181.36 kg P. The TP to the sediment model shows a similar trend to the TN added to the sediment for this farm with a small increase in the first month, followed by a steeper incline for the last two months. Farm TS2 shows the modelled addition of TP to the sediment at 149.13 kg TP. The model shows an increase of 41.5 kg TP in the first 5 days. The rate of addition however reduces after the first 5 days, showing an overall increase of 107.63 kg TP over the rest of the production cycle. Farm TS3 returns the highest result of the 3 with a modelled TN addition of 1277.23 kg. The Powersim output shows an increasing trend over the course of the whole cycle. The three results can be converted into additions of TP per $m^2$ by dividing the additions by the water area in the farm. This resulted in the modelled results showing an input of 32.6 g TP/$m^2$ for TS1, 20.5 g TP/$m^2$ for TS2 and 472 g TP/$m^2$ for TS3. The modelled results suggest that total additions of TP from feed and fertiliser are the main forcing functions in the level of TP added to the sediments. It also indicates that water exchange has a part to play in the TP added to sediments as table 5.1 shows farm TS3 to have the highest additions of feed and also fertiliser followed by TS1 and finally TS3 who adds the least feed and does not add any fertiliser.



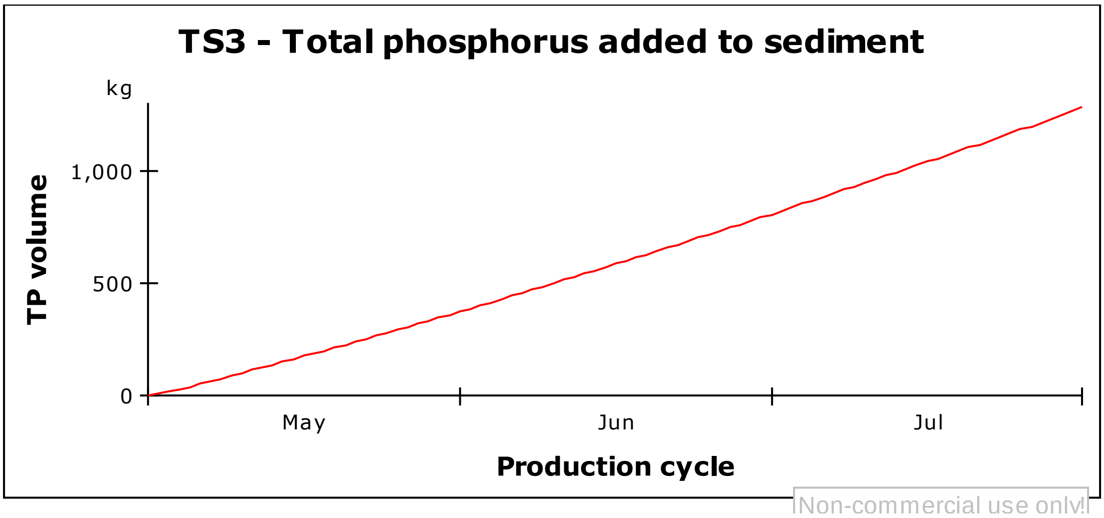
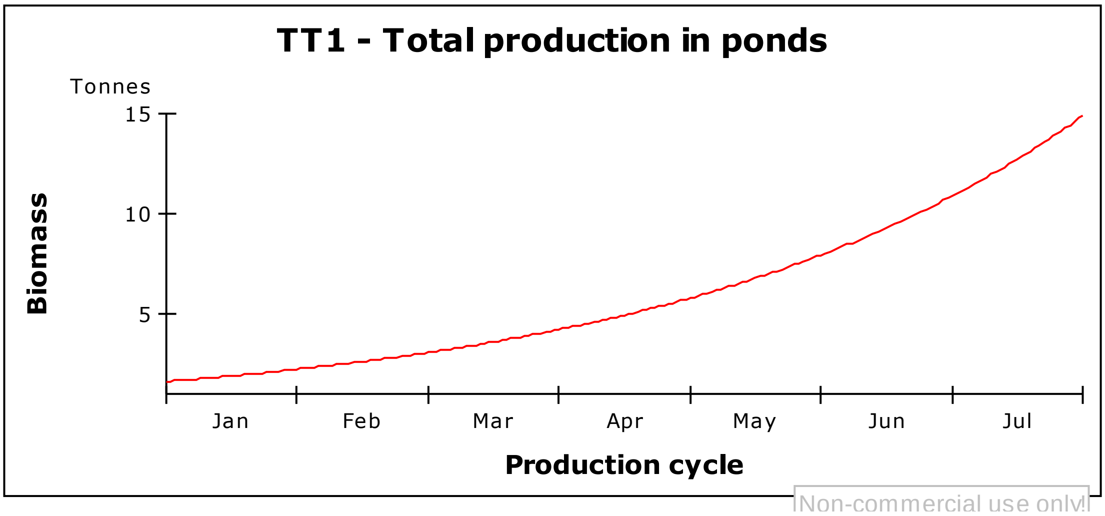



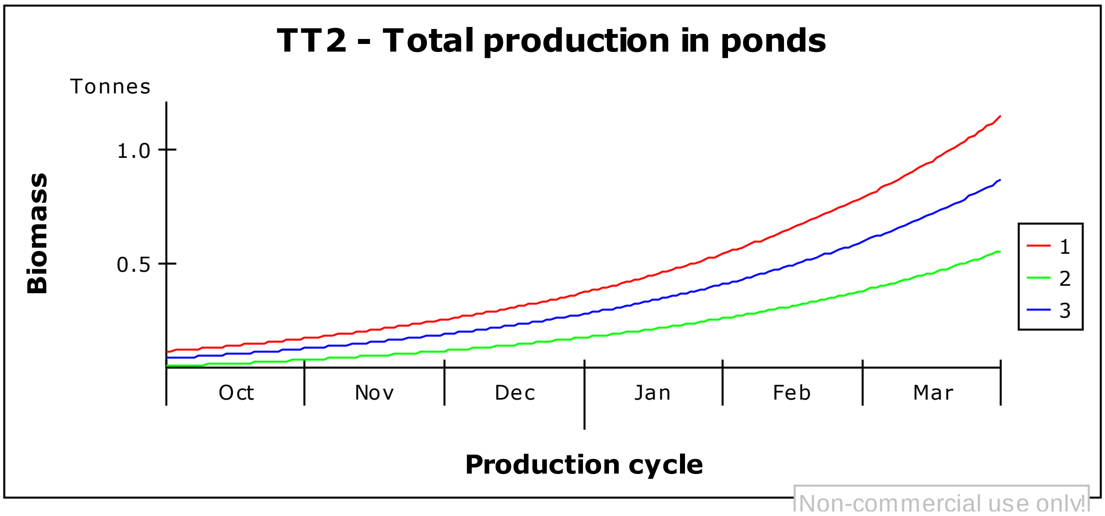

Figure 5.10: Model outputs for TP added to sediments for Thailand case study farms during the culture period (Powersim™ outputs)

### 5.3.2. Thailand tilapia case study model outputs

#### 5.3.2.1 Total production

Tilapia production varies within the case studies. Figure 5.11 shows that TT1 produces a total of 14.94 tonnes of fish from a single pond using a stocking density of 9.4 fish/$m^2$. Of the 3 case study sites it has the lowest rate of mortality at 20% over the whole cycle. TT2 is a 3 pond farm with an average water area of 5047.16 $m^2$ per pond. The farm is larger than TT1 However it uses a much lower stocking density of 0.625 fish/$m^2$, resulting in a total production of 2.56 tonnes for the farm overall with a minimum production value of 558.49 kg to a maximum of 1139 kg per pond. TT3 is the largest of the 3 farms, containing 7 grow out ponds with an average water area of 1803.83 $m^2$. The production model for the farm shows an output of 27.8 tonnes of product even with a mortality rate of 60%. Farm TT3 shows a modelled minimum and maximum production value of 3.16 tonnes and 4.76 tonnes across the 7 ponds. TT2 shows much lower modelled production values than the other two case studies. This is due to the low stocking density of 0.625 used in comparison to the other 2 farms (TT1 and TT3) which use 9.4 individuals/$m^2$ and 6.25 individuals/$m^{2.}$



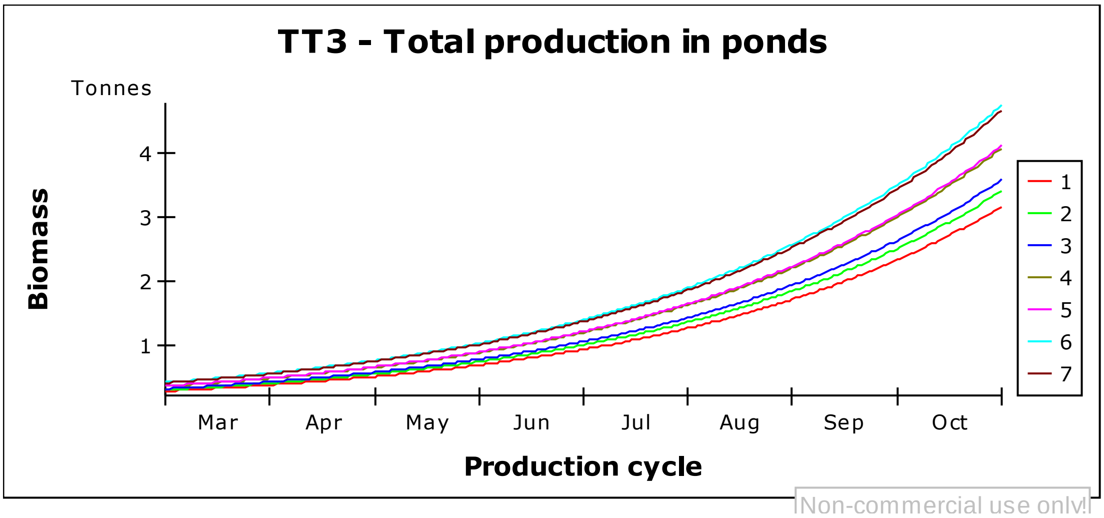



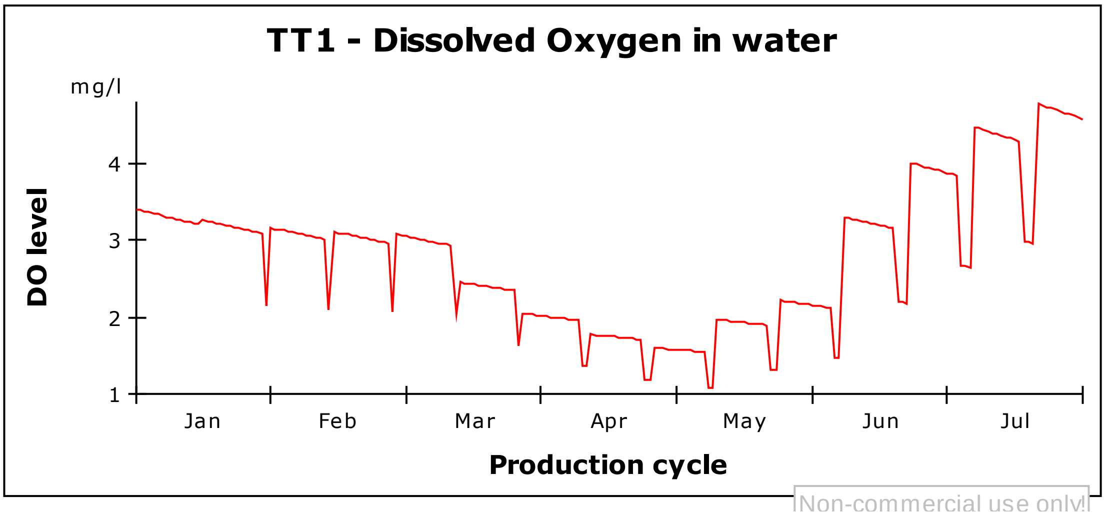

Figure 5.11: Total modelled production in three case study farms for Thai tilapia over a production period (TT1- 1 pond; TT2- 3 ponds: TT3- 7 ponds) (Powersim$^{TM}$ output)

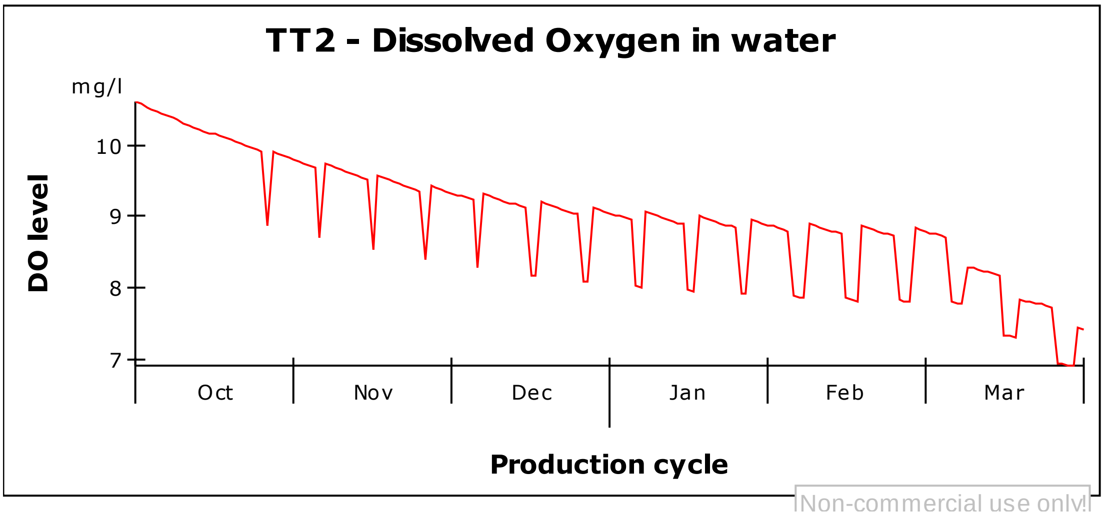
#### 5.3.2.2 Dissolved Oxygen

The dissolved oxygen component of the model provided results for DO levels in the water of each farm. The farm level was used to estimate the total level of DO leaving the farms at the end of a cycle to help understand the overall impact the farm has on the surrounding environment. Using the source water for the initial level, the results provided are based on the effects of the use of aeration or not and the implications of water exchange. Farms TT2 and TT3 in figure 5.12 show a decrease in the DO levels over the production cycle, however the degree of reduction varies with each farm, whereas TT1 shows an initial decrease followed by a large increase. The negative spikes in the graphs are not considered to be of concern as they represent the flushing out period of the water causing disturbance. The remaining water is topped up increasing the DO level the same day. The modelled DO level shows a small decrease between water exchange events throughout the cycle, however there is a large variation in the modelled DO over the course of the cycle. The first two and a half months of the cycle show a relatively stable DO level (excluding water exchange activities) with only a change of 0.5 mg DO/l. by mid March the level drops to 2.43 mg/l, explained by the change in the recorded DO level in the source water used during water exchange. The following three water exchange events result in a modelled level of 1.57 mg/l being reached. This then shows an increase over the rest of the cycle to reach a final level of 4.58 mg/l, which can be attributed to the increase in the recorded level of DO in the source water used during water exchange (increases to 6.1 mg/l). The DO in water in this farm is below the recommended limit for good water quality (GAA, 2014) and may result in reduced production values in farm TT1.

Farm TT2 shows an overall reduction in DO from the start time to finish of 3.19 mg/l; however the water exchange process appears to keep the modelled DO level within the ponds relatively stable over months 4 and 5 of the cycle. By month 6 the DO level in the supply water was recorded to be 5.4mg/l potentially causing a decrease in modelled DO level during the last month of the cycle. The DO level within TT2 did not drop enough to be of concern for tilapia survival and stayed above 7 mg/l until harvest.

TT3 shows an overall decrease in the modelled DO level of 3.01mg/l. The modelled DO level is shown to decrease slightly between March and June from 7.4 mg/l to 6.71 mg/l. June to August saw a rise in DO levels, due to the increase in the DO level recorded in the water supply at 9.0 mg/l, which then fell to 2.9 mg/l in August, represented by the drop off from August in the modelled DO level for the farm. Although there was a large drop in DO modelled towards the end of the cycle, the level in the ponds does not quite reach the lower limit for tilapia, this may be attributed to the use of aerators in the farm combined with the initial high levels of DO introduced in the supply water.



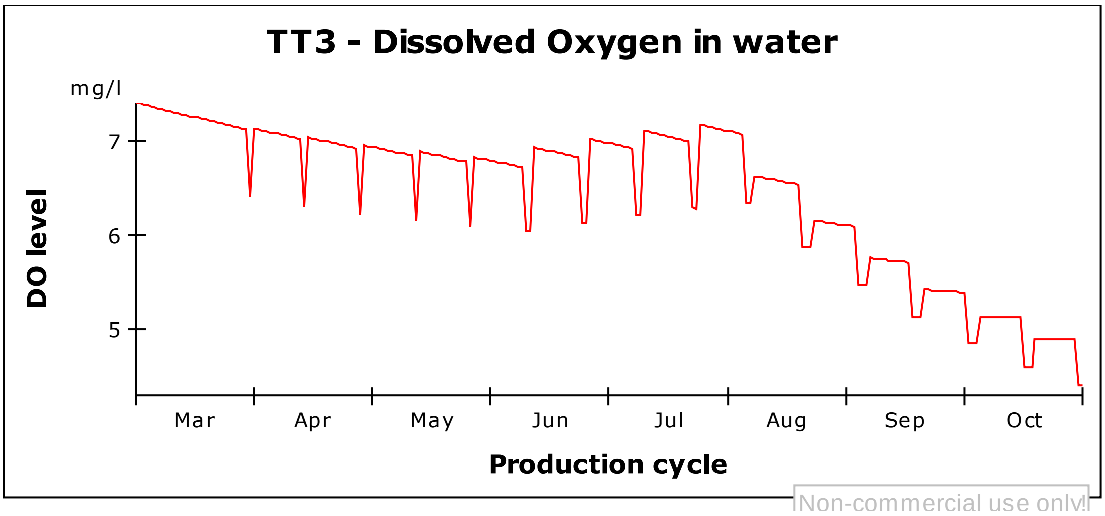




Figure 5.12: Model outputs for DO levels in pond water for tilapia ponds used in Thailand case study farms during the culture period (Powersim$^{TM}$ outputs)

#### 5.3.2.3 Total Nitrogen in water

The following models show the fluctuations of TN levels in the water of individual ponds in the case study farms (fig 5.13). Each case study shows a different dynamic throughout the course of the cycle. Farm TT1 shows an overall increase of the modelled TN over the course of the cycle. The modelled TN increases only slightly in the first 3 months from 4.16 mg/l to 4.52 mg/l. There is then a steeper increase in the level from May to the end of the cycle of 2.62 mg/l modelled TN from 5.73 mg/l to 8.35 mg/l. This can be explained by the change in the recorded level of TN in the source water from 4.16 mg/l to 6.68 mg/l, which is used in water exchange , increase in water TN levels added to the farm.

Farm TT2 shows a relatively steady level of TN in the water (excluding water exchange) for the first four months of the cycle, with a decrease occurring in the last 2 months. Although there is only a small difference in the TN levels between the ponds (maximum of 4.37 mg/l and minimum of 3.93 mg/l), pond 2 shows a higher level than the others, which show similar results, from midway through the third month. This is due to the similarity in pond size for ponds 1 and 3 at 6731.81 $m^2$ and 5109 $m^2$, whereas pond 3 is approximately half the size of these at 3300.68 $m^2$ resulting in less of a volume for TN levels to disperse over.

Farm TT3 shows an increase in TN levels in the ponds over the whole cycle. the first two months return a small increase in the modelled level of TN in the water for all ponds in the farm from 3.04 mg/l to 3.31mg/l. There then is then a steeper increase for all ponds on the farm for months four and five, followed by a slowing of the rate of increase in the final three months to a final average point of 5.65 mg/l, with a maximum of 6.25 mg/l and a minimum of 5.18 mg/l in the ponds. This trend can be explained by the change in recorded TN level n the source water used during water exchange from 3.04 mg/l to 4.48 mg/l and back to 3.31 mg/l.

The order of the case study farms in relation to the modelled TN level in the water goes TT1, TT3 and TT2. This can be explained through the level of feed added to the system coupled by the TN level in the source water, driving the changes in the TN dynamics throughout the cycle.

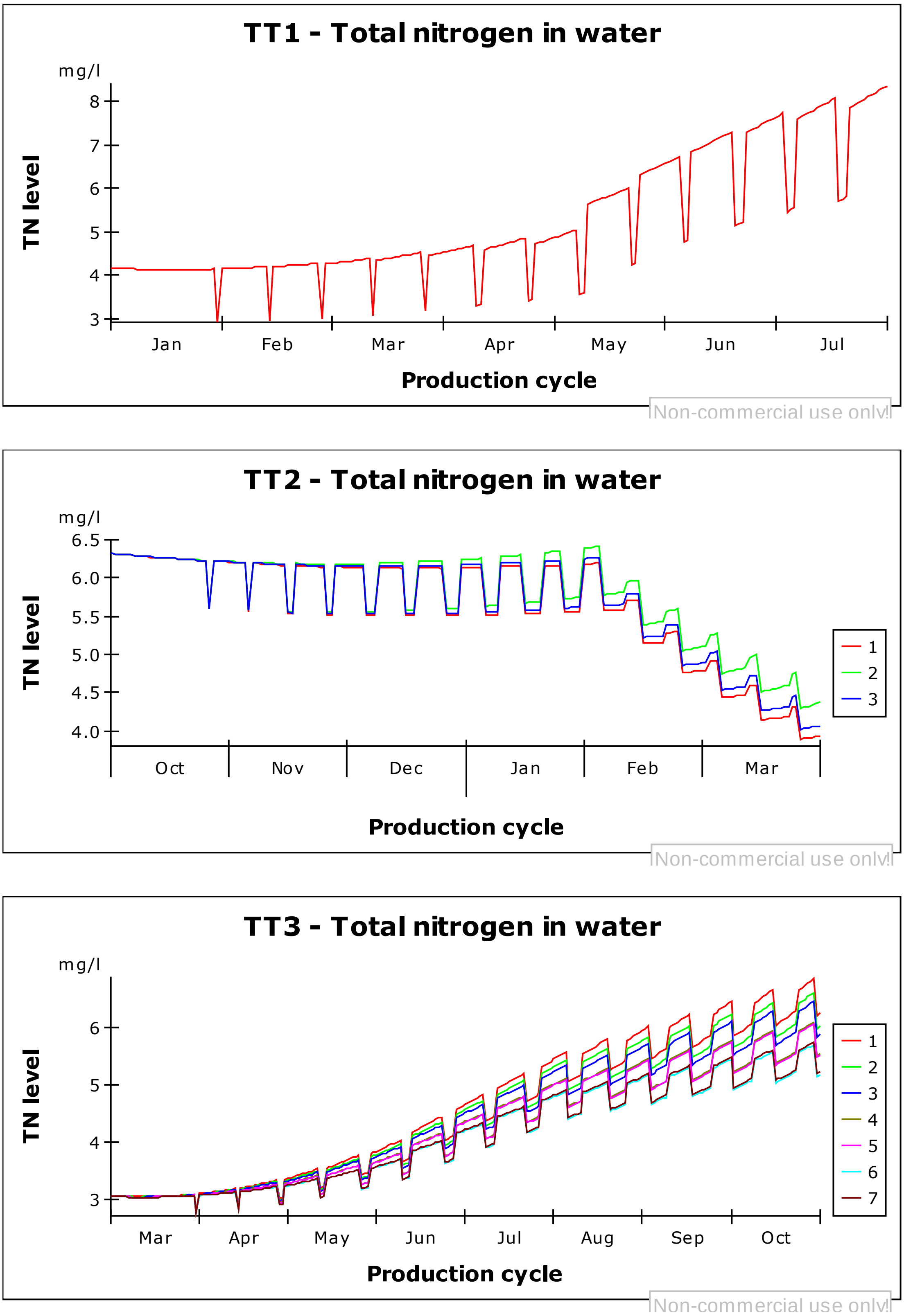
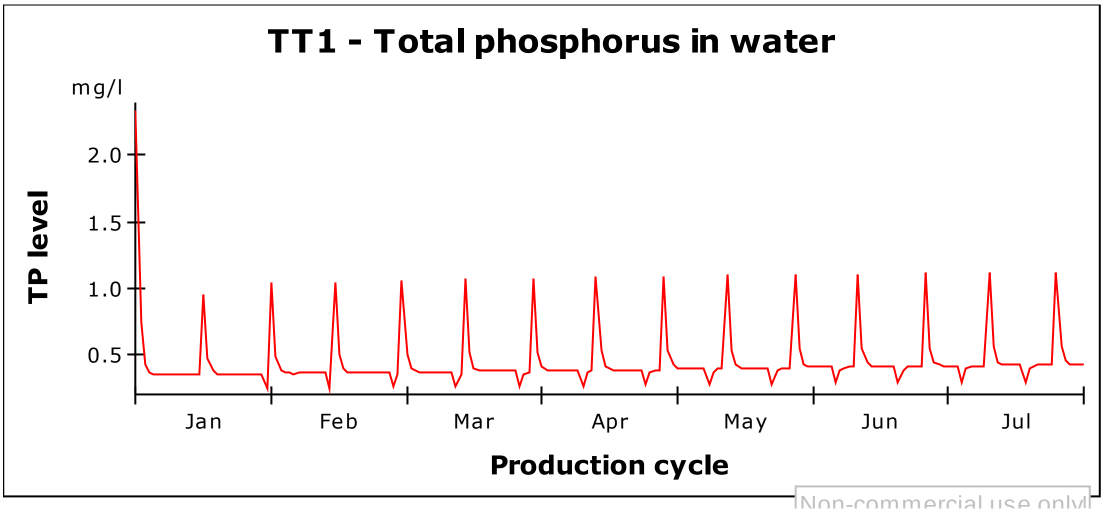


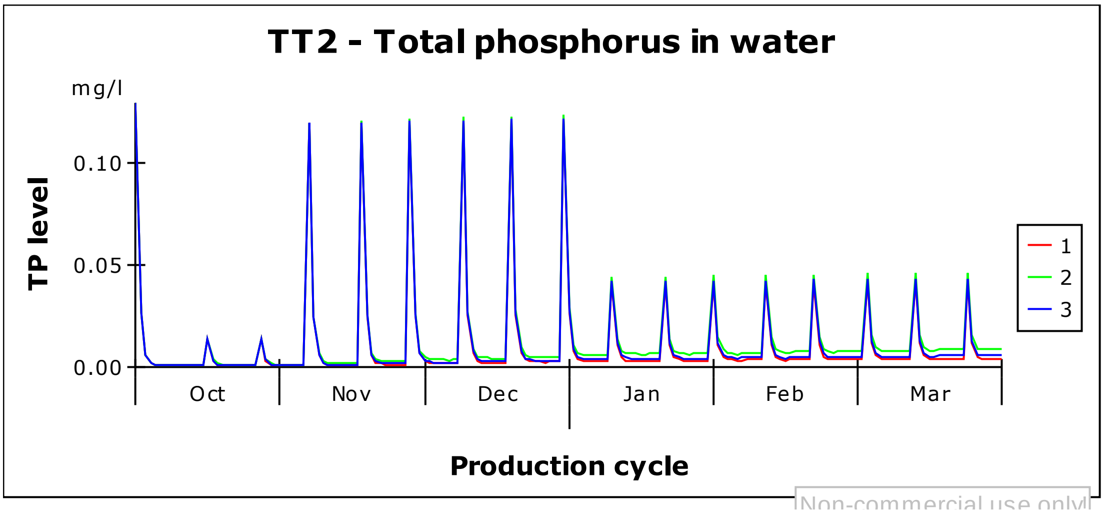

Figure 5.13: Model outputs for each Thai tilapia farm representing the total nitrogen in the water of each pond (Powersim$^{TM}$ output)

#### 5.3.2.4 Total Phosphorus in water

Total phosphorus levels in the farms vary and appear to depend on the level of TP recorded in the source water, except in the case of TT3. This is shown in figure 5.14 where a spike, either positive or negative, is shown at the point of water exchange.). TT1's source water appears to have the highest recorded TP level at 2.34 mg/l. The area in which the farm is located contains a high density of aquaculture sites that may be contributing to the higher level of TP in the source. The TP level in TT1 reduces in the first few days from 2.24mg/l to 0.35mg/l, which then increases with the 1$^{st}$ water exchange event to 0.98mg/l, indicating that the largest source of TP is the source water surrounding the farm. TT2 has a level of TP which is low at the beginning of the cycle when there was 0.13 mg/l TP measured in the source water, which increases to 1.19mg/l in source water resulting in a pond TP level of 0.12mg/l. This is an increase of 0.119 mg/l from the lowest point in October. The graph indicates that source water has a significant effect on the quality of the water in the farms as, by January the source water has reduced to 0.38 mg/l, reducing the level entering the farm. However figure 5.14 also shows that the TP level in-between water exchange is also increasing.

Farm TT3 shows a decreasing trend in modelled TP levels throughout the cycle. The Powersim output shows a decrease over the first six months from 0.34 mg/l to 0.25 mg/l, the final two months show a slight increase from 0.25 mg/l to 0.26 mg/l an increase of only 0.01mg/l. This is most likely due to the increase in phosphorus levels in the feed from 0.01% to 0.98% in June as the recorded level of TP in source water decreased from 0.27mg/l to 0.25 mg/l in the same period.



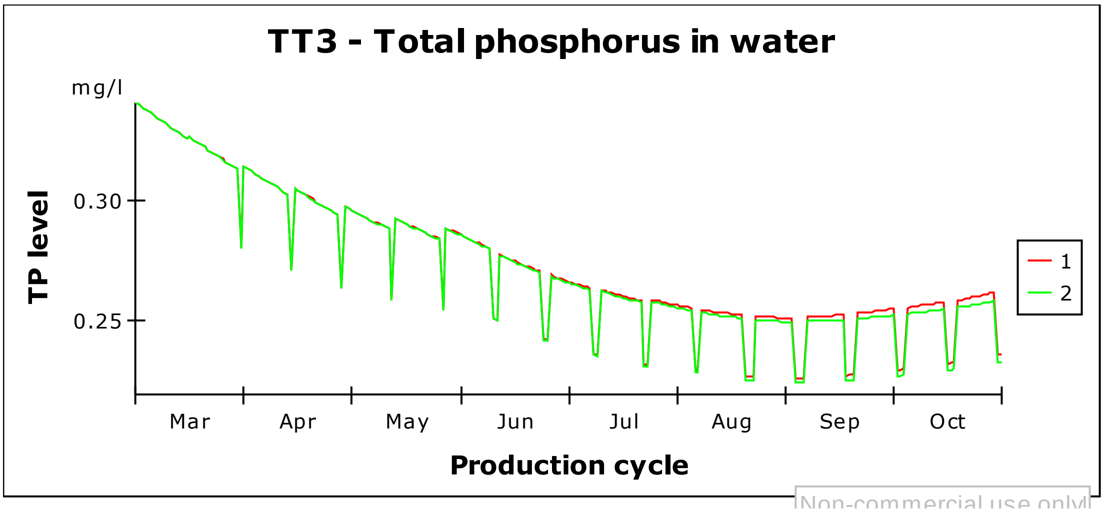




Figure 5.14: Model outputs for TP levels in each pond in the Thai tilapia farms (Powersim™ output)

### 5.3.2.5 Total Nitrogen in sediment

Total nitrogen level added to sediment, in all farms, is shown to increase in figure 5.15. TT1 shows a total loading of 113.30 kg for the whole farm, resulting in inputs of 19.2 g /$m^2$. The farm shows a modelled increase in the addition of TN added to the sediment which slows in the rate of addition in the last two months of the cycle. This is likely due to the reduction in TN recorded in the feed added from 7.23% to 2.71% as the TN level recorded in the water source shows an increase over the last 3 months of the cycle. TT2 shows a total modelled loading of 27.71 kg for the entire farm, equating to 1.8 g/$m^2$. The rate of addition is relatively steady until the last two months where there is a very small change, reducing the rate of addition of TN. The level of TN in the feed level does not change over the cycle, however the level of TN recorded in the water source shows a decrease from 6.32 mg/l to 1.25 mg/l which ay be contributing to the reduced rate. TT3 has a modelled loading of 24.42 kg, equating to 1.93 g/$m^2$. Just as in farm TT1 the percentage of TN recorded in the feed reduced from 7.29% to 4.19%, providing a possible explanation for the slowing of the rate of addition after the first three months of culture.

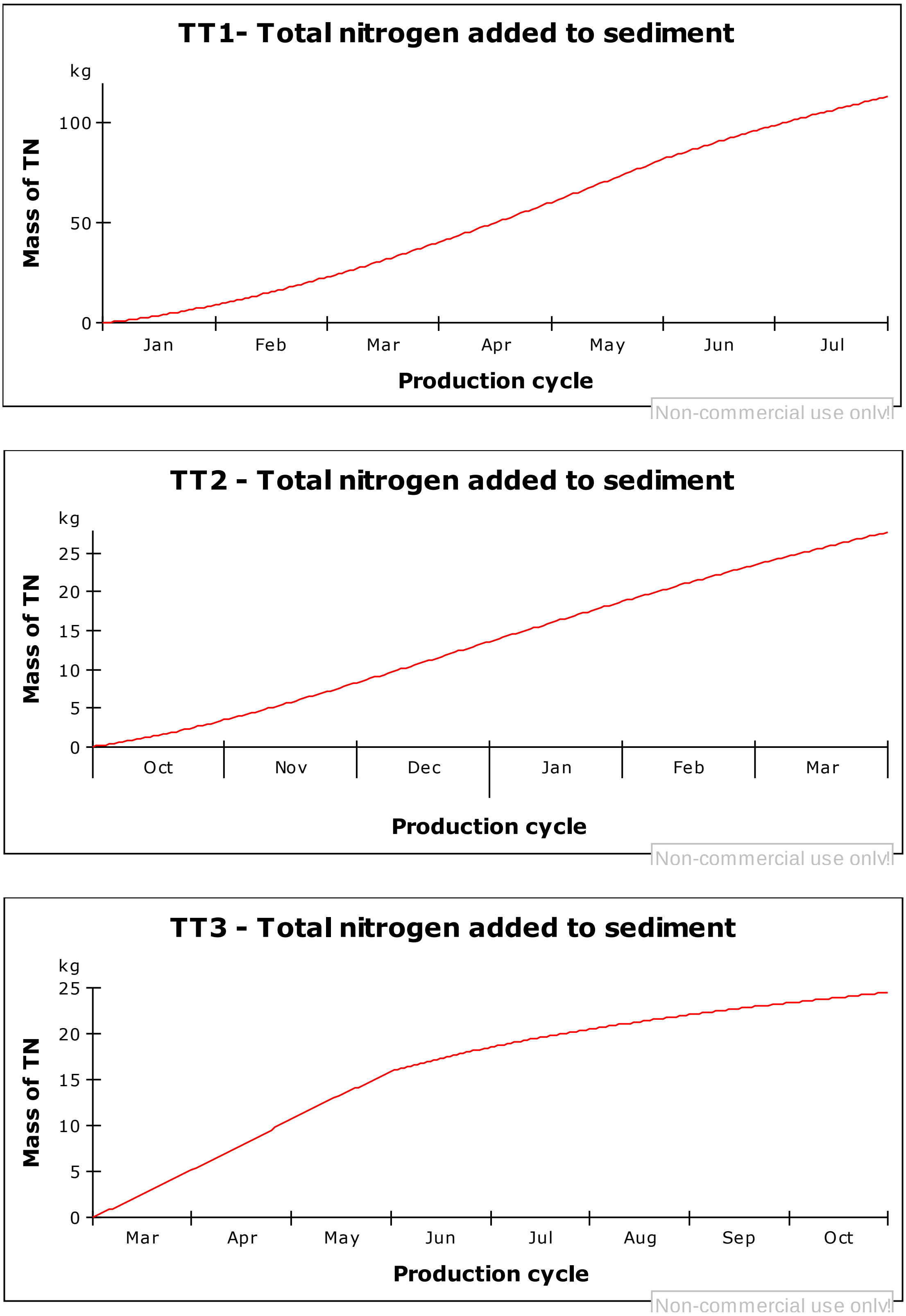
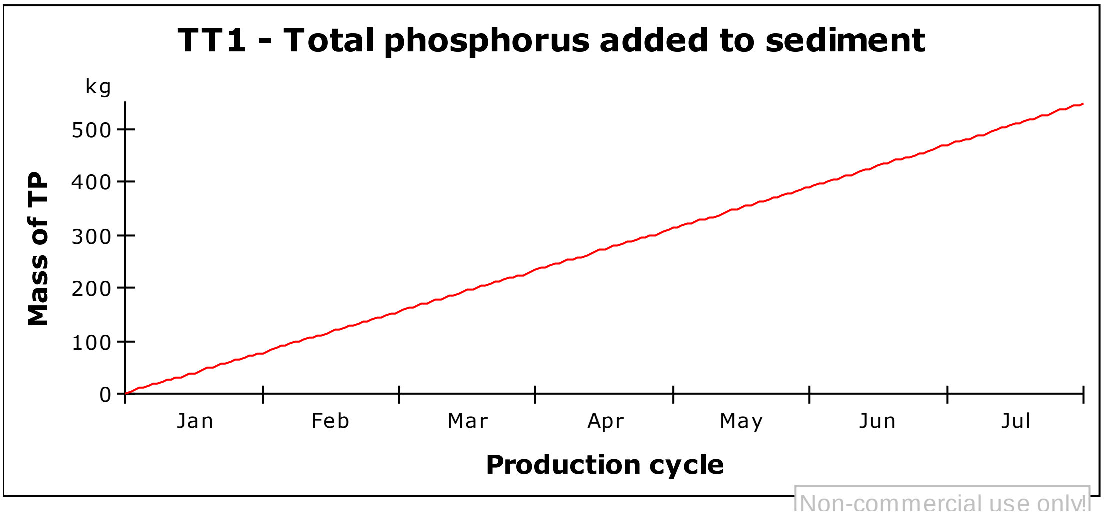
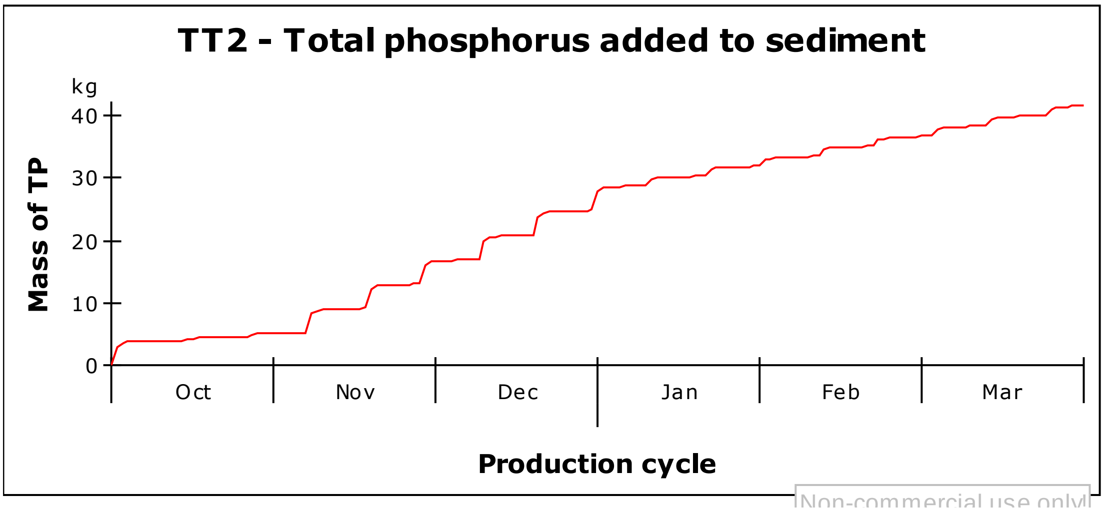



Figure 5.15: Model outputs for TN added to sediments for Thailand tilapia case study farms during the culture period (Powersim$^{TM}$ outputs)

#### 5.3.2.6 Total Phosphorus in sediment

Phosphorus is considered to have a high affinity with the bottom soils of aquaculture ponds. The modelled outputs for TP added to the sediment represent the additions to the farm as a whole and not individual ponds (fig 5.16). Farm TT1 is shown to have a total loading of 548 kg resulting in inputs of 92.7 g/m$^2$. The trend shown in the Powersim output indicates steady rate of additions to the sediment of modelled TP. This may be due to there being no large change in the TP level in the feed and very little change in the level in the source water (0.81 mg/l to 0.74 mg/l). TT2 has a total loading of 41.44 kg with an input of 2.74 g/m$^2$. This trend shows a step wise increase of modelled TP additions to the farm. The change in recorded TP content of feed is very little pointing towards the TP content of the source water used for water exchange as the cause. The stepwise change coincides with the water exchange events on the farm and the increase of TP recorded in water rises from 0.13 mg/l to 1.19 mg/l causing a rise in the modelled TP added to the sediment, the rate of addition slows in the last three months of the cycle as the water TP decreases to 0.38 mg/l. Farm TT3 shows a total loading of 12.79 kg resulting in an input of 1.013 g/m$^2$. The first three months of the cycle see a slow rate of addition to the sediment of modelled TP (1.69 kg), followed by an increased rate resulting in an addition of 11.1 kg of TP over the final five months. This change in the rate of addition can be attributed to the change in recorded TP in feed from 0.01% to 0.99%.



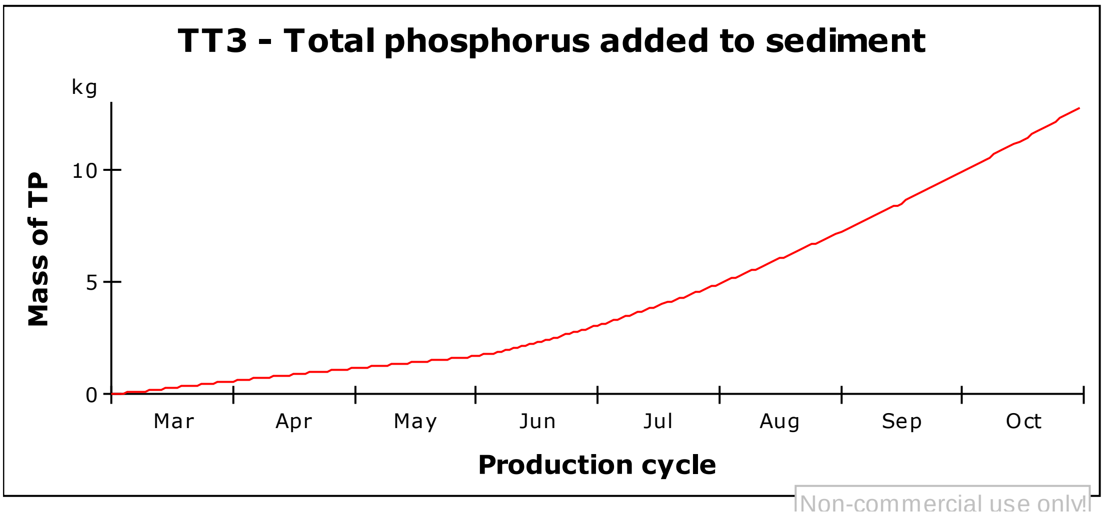
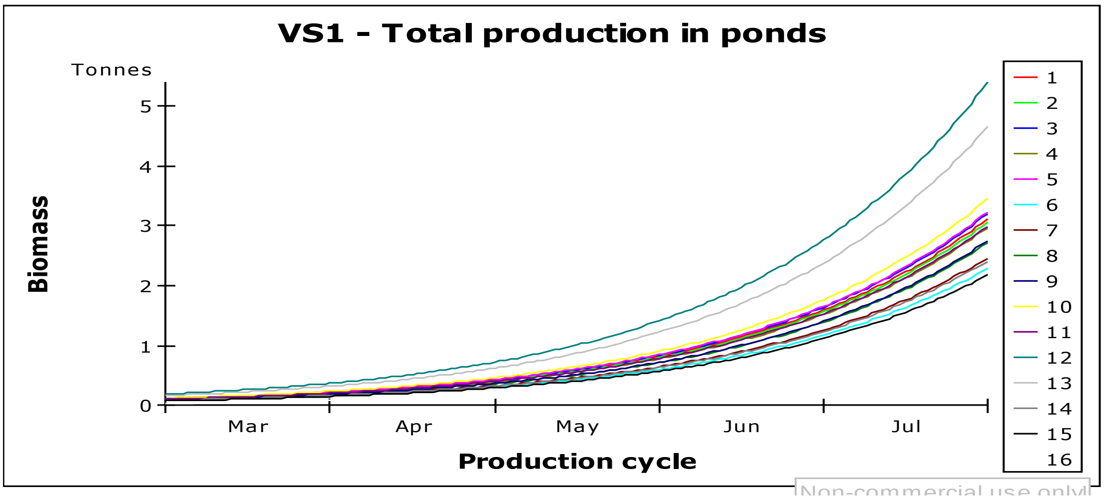



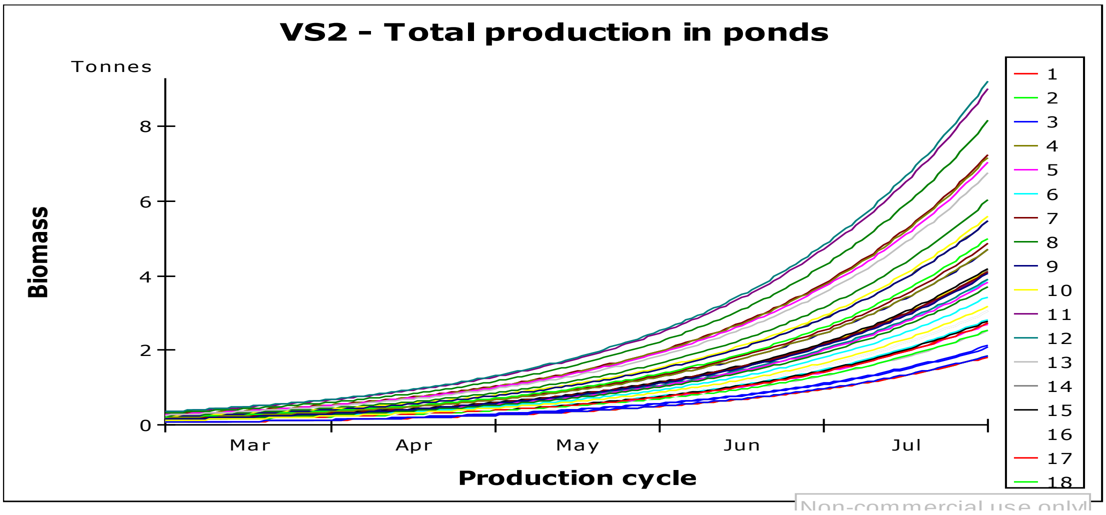

Figure 5.16: Model outputs for TP added to sediments for Thailand tilapia case study farms during the culture period (Powersim™ outputs)

### 5.3.3. Vietnam shrimp case study model outputs

#### 5.3.3.1 Total Production

Figure 5.17 shows the modelled production for each farm in each of the ponds. The number of ponds varies between the 3 farms (Table 5.2). VS1 shows a total production of 48 tonnes with a minimum and maximum production of 1.12 and 5.4 tonnes respectively, over 16 ponds with a mortality rate of 25%. VS2 produces 180.38 tonnes over the course of a cycle for 42 ponds with a mortality rate of 37%. The maximum production for 1 pond in this farm is 9.21 tonnes with a minimum of 1.83 tonnes with an apparent SGR of 2.42 %/day. VS3 shows a total production over this cycle of 4.81 tonnes with a maximum and minimum of 1.85 tonnes and 0.26 tonnes over 5 ponds resulting from an SGR of 2.9 %/day. This farm reports a mortality rate of 10%.



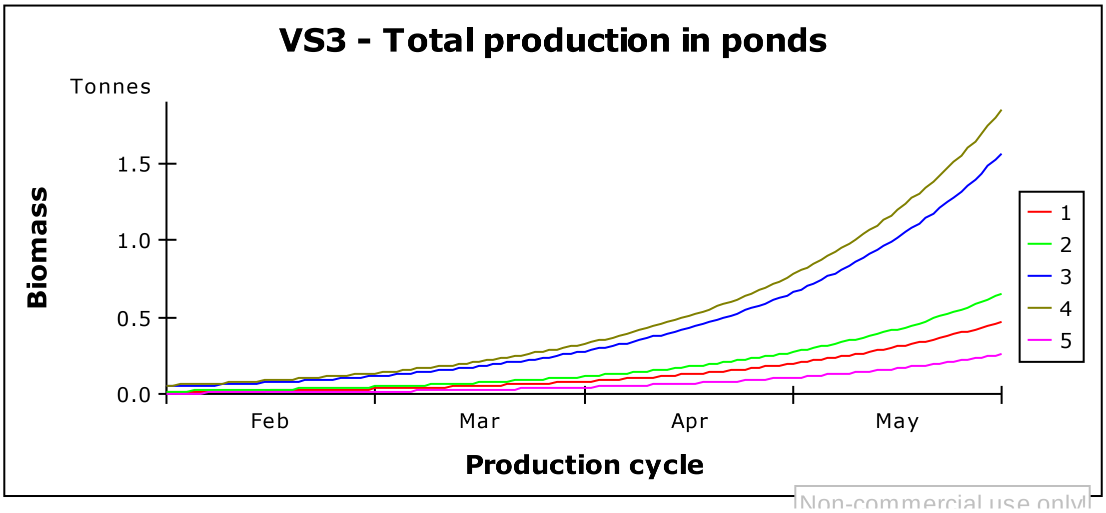



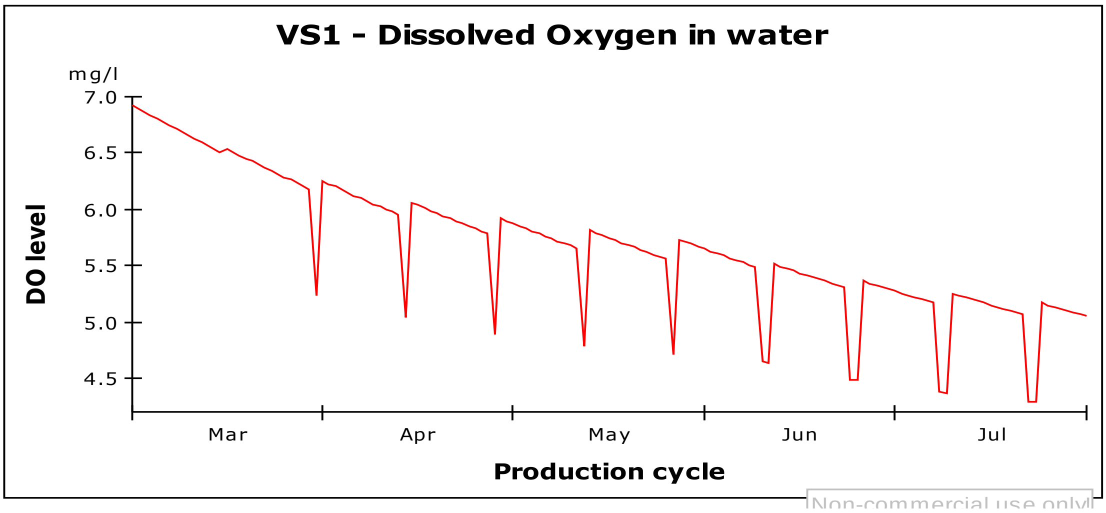

Figure 5.17: Total modelled production in three case study farms for Vietnamese shrimp over a production period (VS1- 16 ponds; VS2- 42 ponds: VS3- 5 ponds) (Powersim$^{TM}$ output)

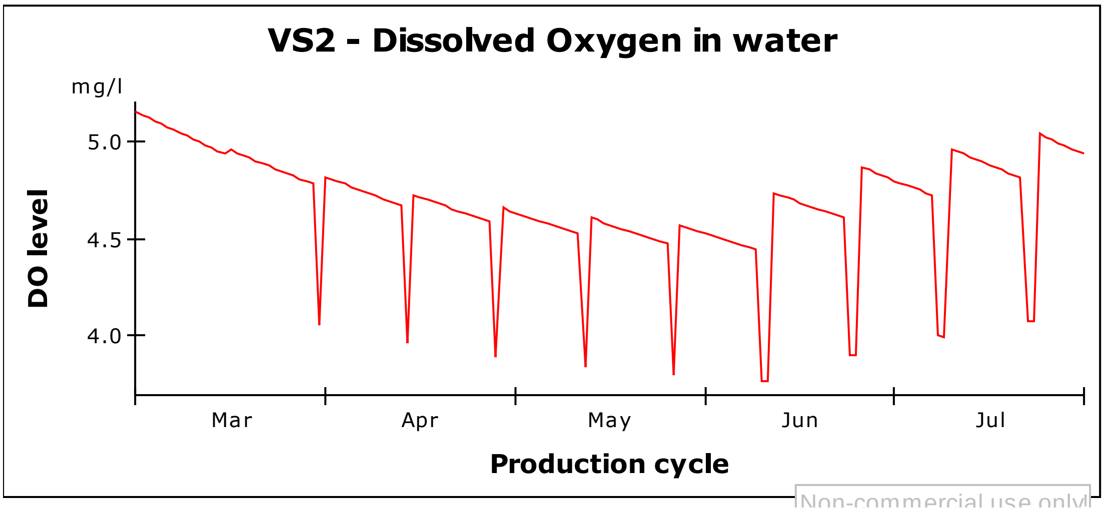
#### 5.3.3.2 Dissolved Oxygen

Dissolved Oxygen is shown to reduce over the course of the cycle for farms VS1 and VS3 (Fig 5.18). VS2 however shows a slight increase in DO from June to the end of the cycle. VS1 has an overall decrease in DO from the start of the cycle to harvest of 1.96mg/l from 6.93 to 4.97 mg/l, however the month of June showed a drop in the supply DO level from 6.93mg/l to 5.92 mg/l. This results in a difference from the source water of 0.95 mg/l. VS1 shows a minimum DO level of 4.21mg/l during water exchange.

The DO level in VS2 decreases from the beginning of the culture cycle, where the source water contained 5.15mg/l, to the end of the cycle, which modelled a final level of 4.93mg/l. The model accounts for the change in the DO in source water from 5.15 to 6.47mg/l, represented by the increase in pond DO from June.

VS3 shows a decrease in DO of 0.56mg/l. The source water is recorded as containing 4.88mg/l. The output for VS3 reports the farm to reach the lowest DO during water exchange of all the farms (3.4mg/l). This is close to the limit regarded as a lower limit for good water quality in pond culture for many groups. Water exchange is shown to increase the DO level in the water by adding a fresh supply of DO from the source water for all farms. According to the model all farms would manage to maintain a DO level above 4.0mg/l, except during the flushing out of water for exchange purposes, however as the water is topped up during in the same day, the time shrimp are exposed to low DO levels is limited.



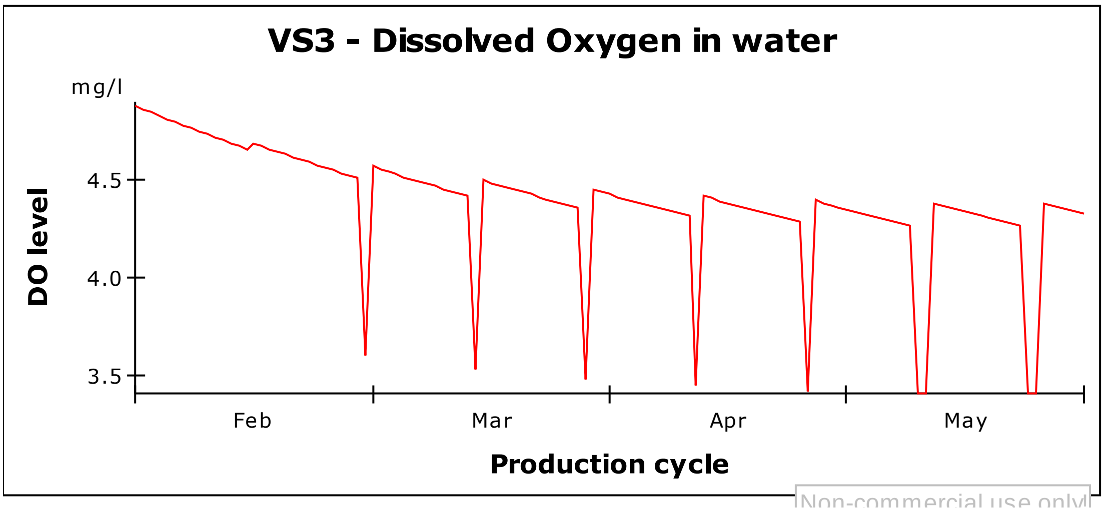



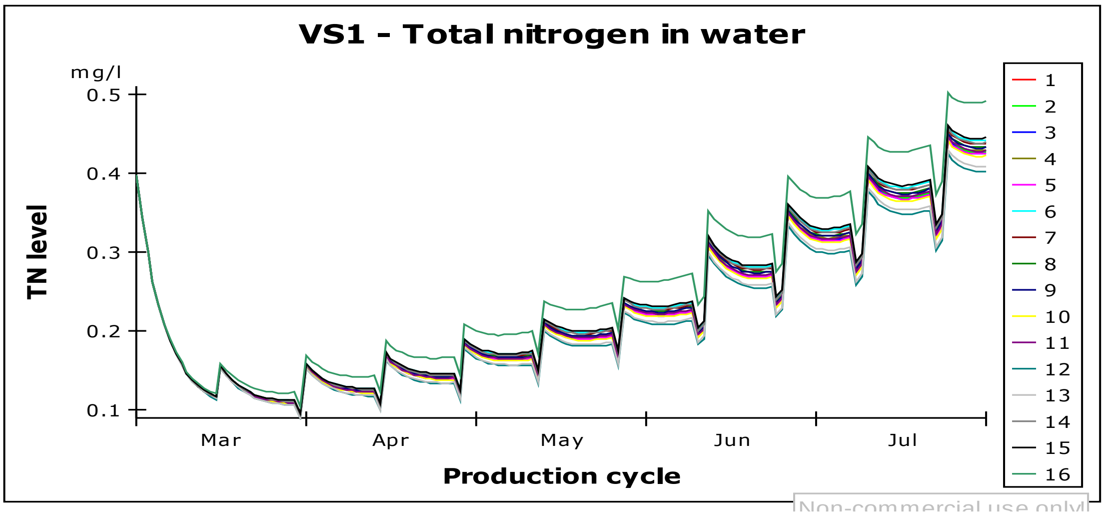

Figure 5.18: Model outputs for DO levels in pond water for shrimp ponds used in Vietnamese case study farms during the culture period (Powersim$^{TM}$ outputs)

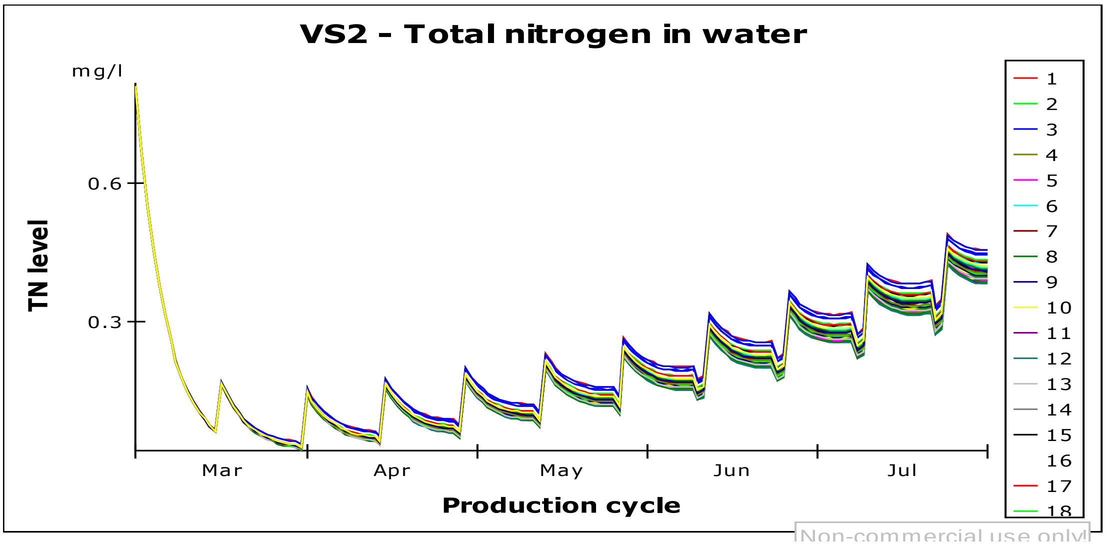
#### 5.3.3.3. Total Nitrogen in water

The following Powersim outputs show the fluctuations of modelled TN levels in the water for individual ponds at case study farms (fig 5.19). Each case study farm shows an increase in the level of modelled TN in the water over the course of a production cycle, though the dynamics differ between farms. Farm VS1 shows an initial decrease from from 0.40 mg/l of modelled TN to 0.12 mg/l. This is followed by an overall increase of 0.31 mg/l TN. During the time between water exchange the modelled TN level is shown to decrease, however the change in recorded TN in source water from 0.40 mg/l to 0.67 mg/l resuts in a steeper increase in the level of modelled TN in the ponds in the farm. It should be noted that pond 16 shows the highest level of TN in the water. This difference to the other ponds is possibly due to the smaller pond size of 1623.38 $m^2$ resulting in less of a volume for modelled TN to disperse over.

Farm VS2 shows a similar trend to farm VS1. However the initial decrease in modelled TN is larger at 0.75 mg/l. The modelled TN in pond water shows a final average of 0.41 mg/l, with a minimum of 0.38 mg/l and a maximum of 0.46 mg/l. There appears to be no significant change in the rate of the modelled additions of TN to the ponds, which is possibly due to the very slight change in recorded TN levels in the source water throughout the cycle from 0.81 mg/l to 0.86 mg/l.

Farm VS3 again displays the same initial decrease in modelled TN level in the first two weeks of the cycle, with an initial level of 0.90mg/l to an average of 0.19 mg/l in the farm. The modelled TN for the ponds shows a very small increase from the end of the first month of the production cycle to the end from an average of 0.40 mg/l to 0.53 mg/l with a final minimum of 0.49 mg/l and a maximum of 0.59 mg/l. This result is possibly due to no observed change in the recorded source water TN level coupled with no change in the recorded TN content in feed. The farm however does use fertilizers (table 5.2), which may be the cause of the small increase over the cycle.



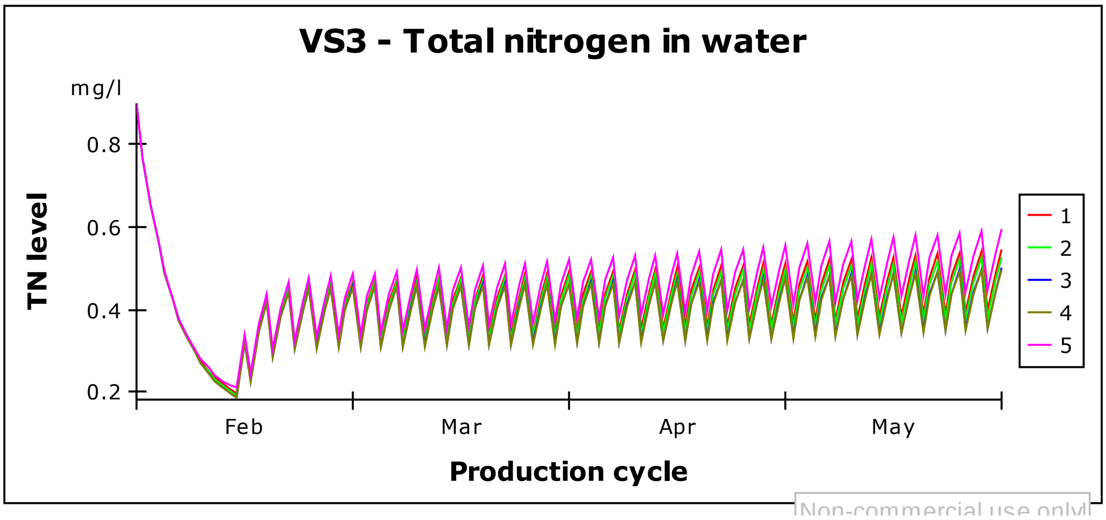




Figure 5.19: Model outputs for each Vietnamese shrimp farm representing the total nitrogen in the water of each pond (Powersim™ output)

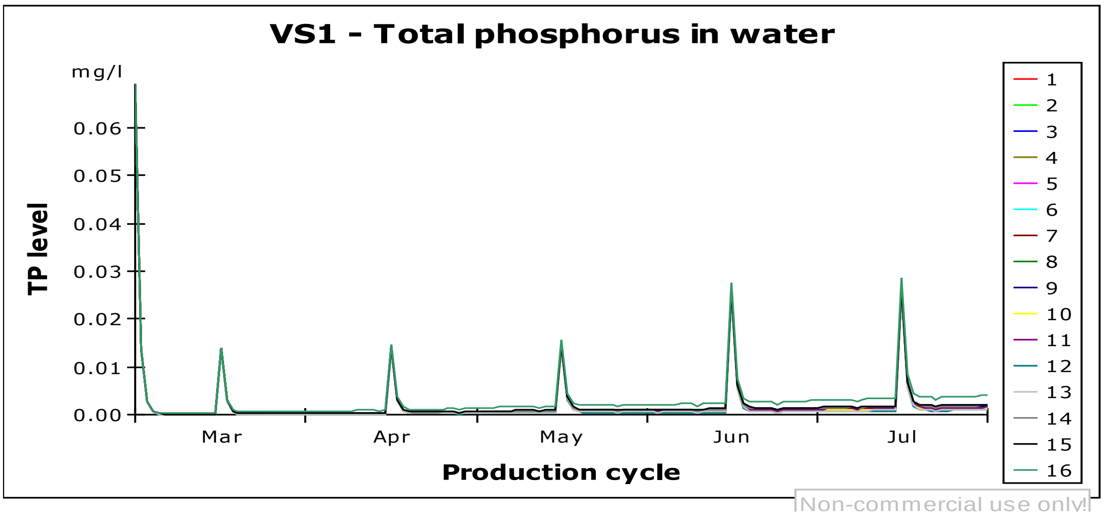
#### 5.3.3.4 Total Phosphorus in water

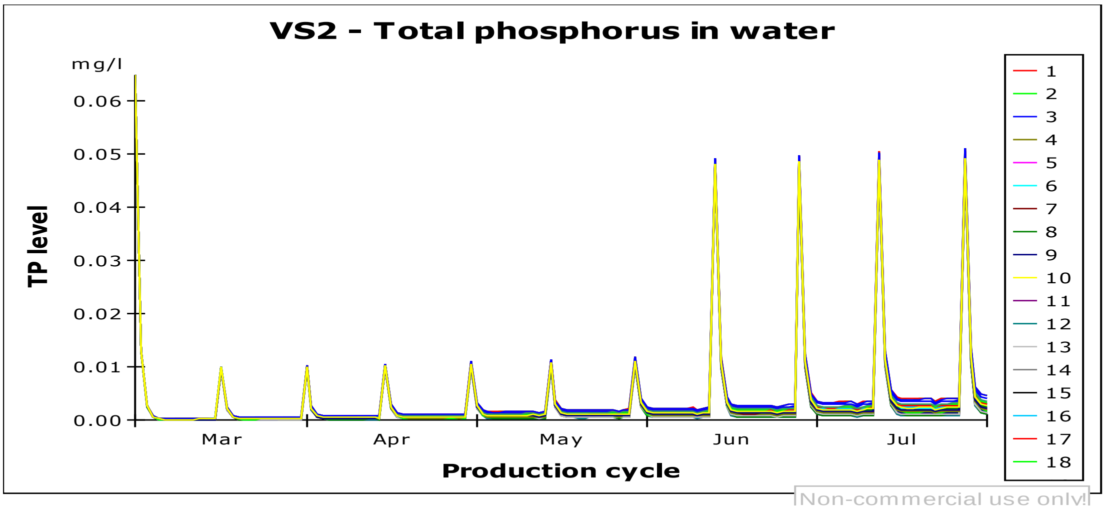
Figure 5.20 below outlines the modelled levels of TP in the water of ponds at the case study farms. All farms show an increase in the level of modelled TP in the water however some show a larger increase than others. The spikes in the graphs produced by Powersim indicate water exchange events.

Farm VS1 shows a decrease in the level of modelled TP for the first few days of the culture cycle. The initial water used to fill the ponds contained 0.07 mg/l TP as recorded. This then decreased to 0.00068 mg/l as modelled. The TP level shows an overall increase to 0.0017 mg/l by the end of the cycle, which is facilitated by the increase in recorded TP in the source water used during water exchange from 0.07 mg/l to 0.31 mg/l.

Farm VS2 shows a similar overall trend to farm VS1. The initial decrease in the first few days totals 0.65 mg/l. there is a small increase over the whole cycle resulting in a modelled average of 0.0025 mg/l, with a minimum of 0.001 mg/l and 0.0046 mg/l. The largest increase occurs in the last two months of the culture cycle possibly due to the increase of the recorded TP in the source water used for exchange from 0.065 mg/l to 0.29 mg/l. It should be noted that the recorded TP content for feed did not change during the culture cycle.

Farm VS3 has again a similar trend to the other two farms, showing a decrease in modelled TP levels at the start of the cycle with an overall increase in TP levels over the course of the cycle. This time, however, the levels of modelled TP are higher than the other two farms providing a better visualisation of the dynamics. Farm VS3 shows the initial modelled decrease to be 0.04 mg/l to 0.08 mg/l. this remains constant, when excluding water exchange action, followed by an increase to 0.15 mg/l. this increase is due to the increase in recorded TP in source water used for water exchange from 0.12 mg/l to 0.31 mg/l. The modelled TP level continues to increase until the end of the cycle resulting in 0.2 mg/l as an average, with a minimum of 0.19 mg/l and a maximum of 0.22 mg /l as modelled.



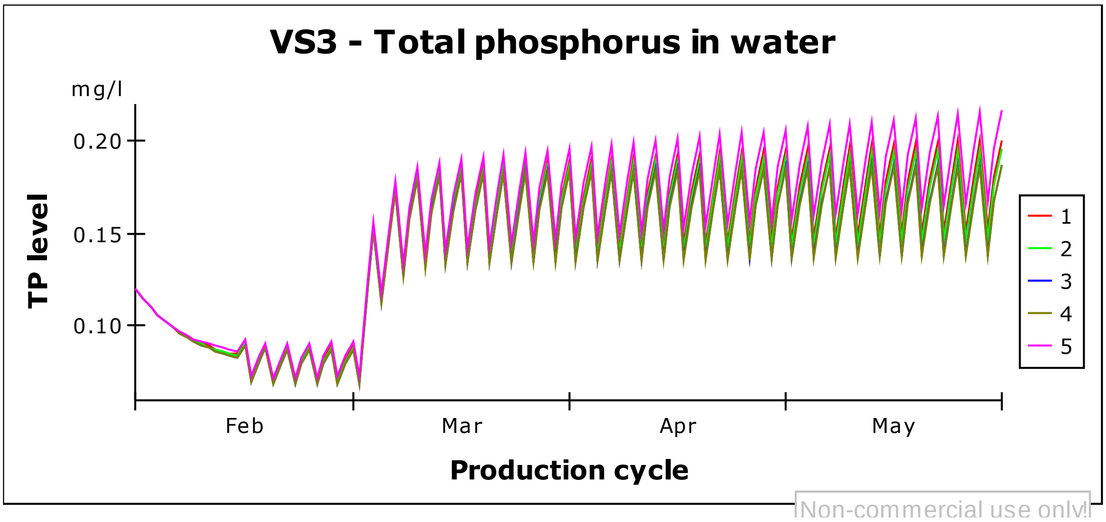
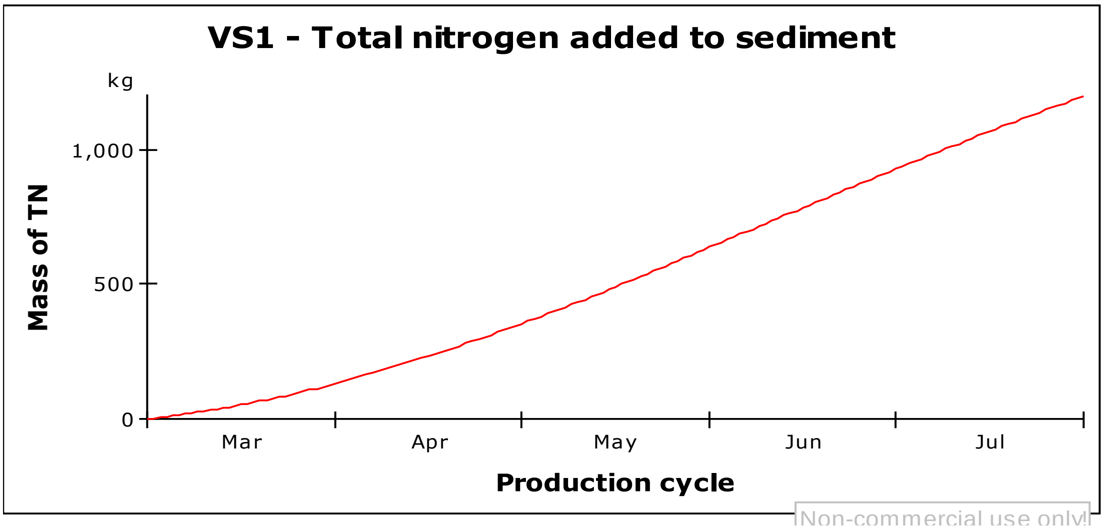



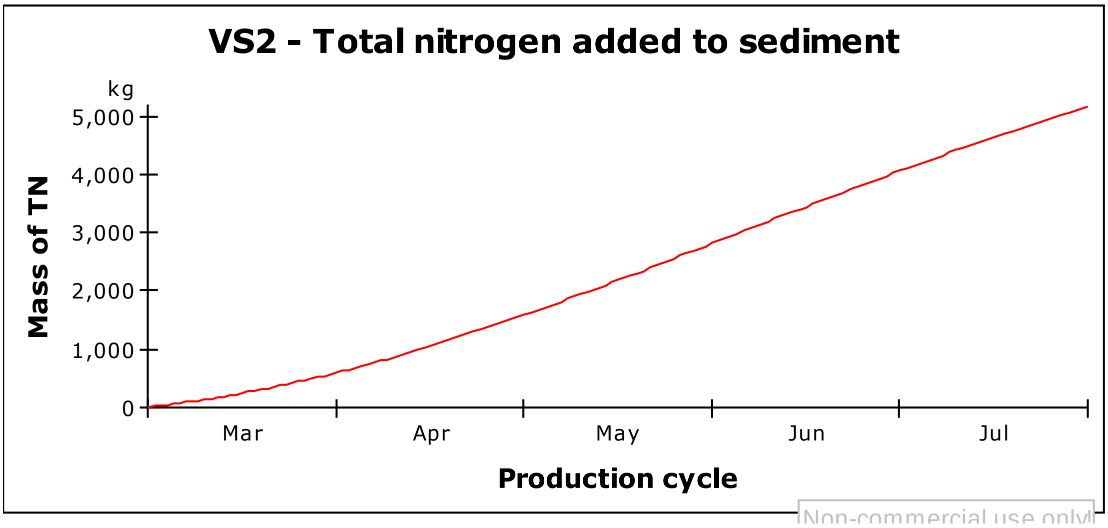

Figure 5.20: Model outputs for TP levels in each pond in the Vietnamese shrimp farms (Powersim™ output)

#### 5.3.3.5 Total Nitrogen in sediment

All farms are shown to fertilise their farms, which can cause an increase in TN levels in the farm as a whole, however the sediments are considered to be nutrient sinks in closed systems (Jamu and Piedrahita, 2002b; Funge-Smith and Briggs, 1998). Figure 5.21 shows the levels of modelled TN collected in sediments for the farms as a whole. Farm VS1 shows a total modelled addition of 1197.21 kg TN ot the sediment. This results in inputs of of 17.23 g/m$^2$. Although the recorded feed levels of TN are higher at the start of the cycle (6.93% to 5.92%) it appears that the rate of addition remains relatively steady. This may be due to the increase in the recorded TN in the water source used for water exchange compensating for the decrease in the recorded feed levels. Farm VS2 shows the highest modelled addition of TN to the sediment at 5170 kg. This results in an input of 21.13 g/m$^2$. The Powersim output for VS2 shows a similar trend to VS1. This may be due to a similar trend in the recorded content of TN in feed versus the recorded TN level in the source water.

Farm VS3 returns a total of 350.02 kg of modelled TN added to the sediment resulting in inputs of 28.22 g/m$^2$. The recorded TN for feed did not change over the course of this cycle. While the recorded TN level in source water varied little (0.01 mg/l). Farm VS3 showed the least amount of modelled TN added to the sediment, however had the highest inputs per m$^2$. This is possibly due to the recorded TN in feed reducing over the course of the cycle for farms VS1 and VS2 compared to Farm VS3 where the recorded TN level in feed remained constant.



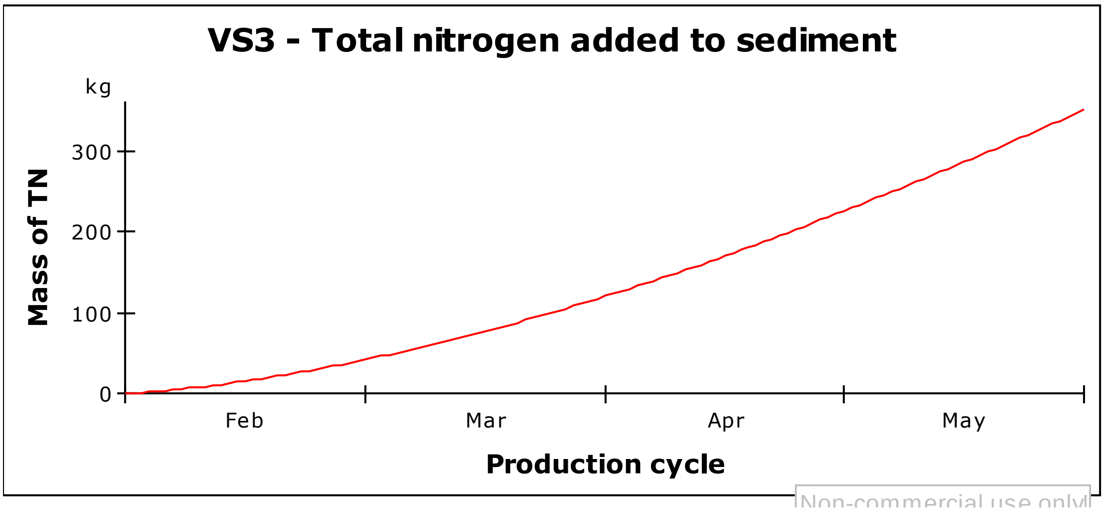
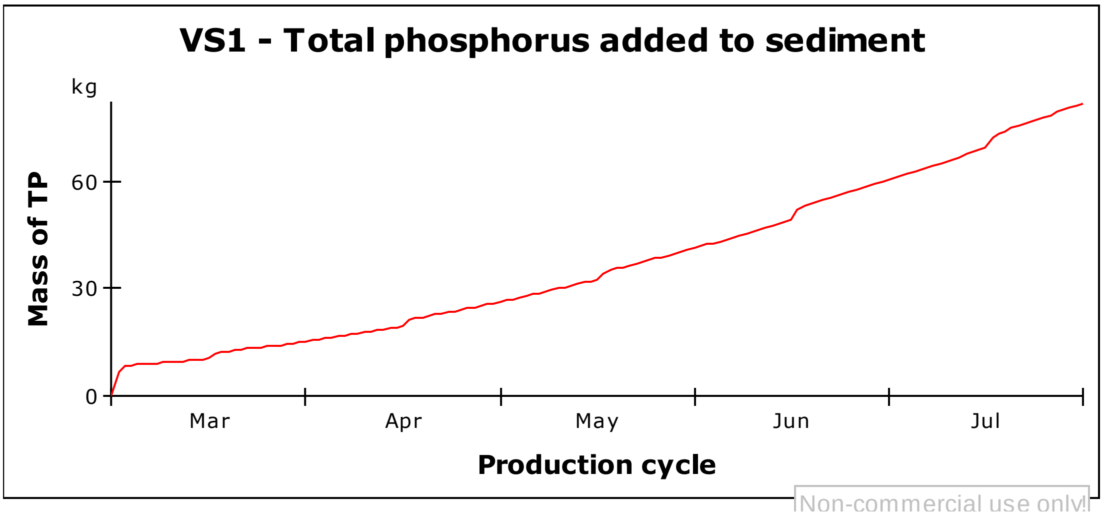
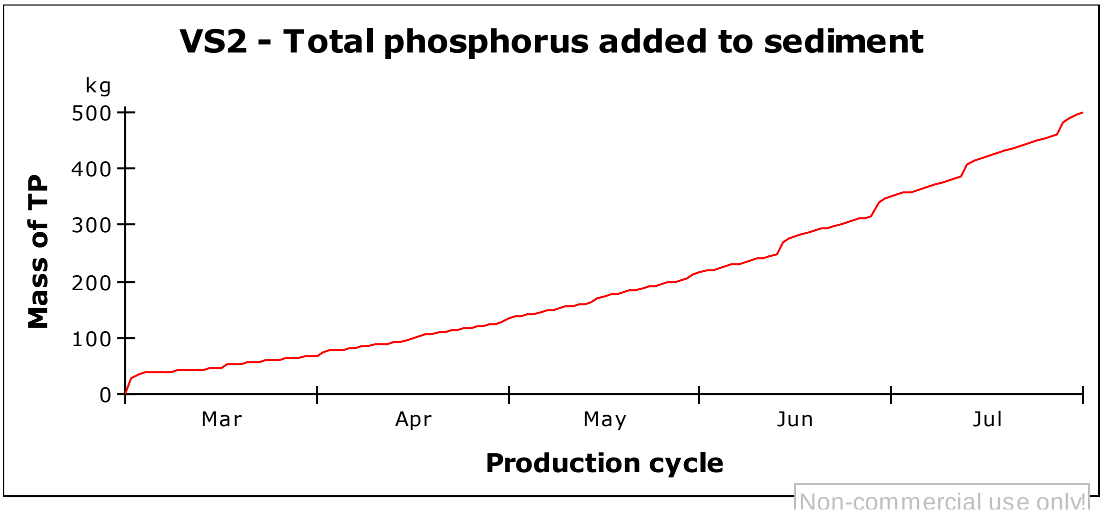




Figure 5.21: Model outputs for TN added to sediments for Vietnamese shrimp case study farms during the culture period (Powersim$^{TM}$ outputs)

#### 5.3.3.6 Total Phosphorus in sediment

The following Powersim outputs show the modelled TP accumulation in sediments at each farm as a whole (fig. 5.22) to help understand the role of the sediment as a nutrient sink. The modelled outputs for all farms show an increase in the amount of TP added to the sediment over the course of the production cycle. Farm VS1 shows a total amount of 81.84 kg modelled TP added to the sediment. This results in a conversion to 1.18 $g/m^2$ added to the sediment. The trend in the increase shows small increases throughout the overall model, which is more evident towards the end of the cycle. This suggests it may be related to the increase in the recorded TP in the source water used for water exchange (0.07 mg/l to 0.13 mg/l) although is not directly linked to water exchange as the increases only occur once per month. The total modelled TP added to the sediment for farm VS2 is shown as 500.02 kg, resulting in inputs of 2.04 $g/m^2$. The farm shows a similar trend to farm VS1 with small increases in modelled TP visible through the cycle. VS2 shows the most visible increase over the last two months where the recorded TP level in the water was shown to increase from 0.065 mg/l to 0.31 mg/l. Farm VS3 shows the total amount of modelled TP added to the sediment as 33.80 kg equating to 2.73 $g/m^2$ of inputs to the farm. The model shows a small rate of increase during the first month of the production cycle with the rate of additions increasing for the remaining three months. While the recorded TP in the feed does not change throughout the cycle, the recorded TP in the water does. The first month shows a source water TP level of 0.12 mg/l which then increases to 0.31 mg/l after the first month, contributing to the change in the rate of increase in the addition of TP to sediment.



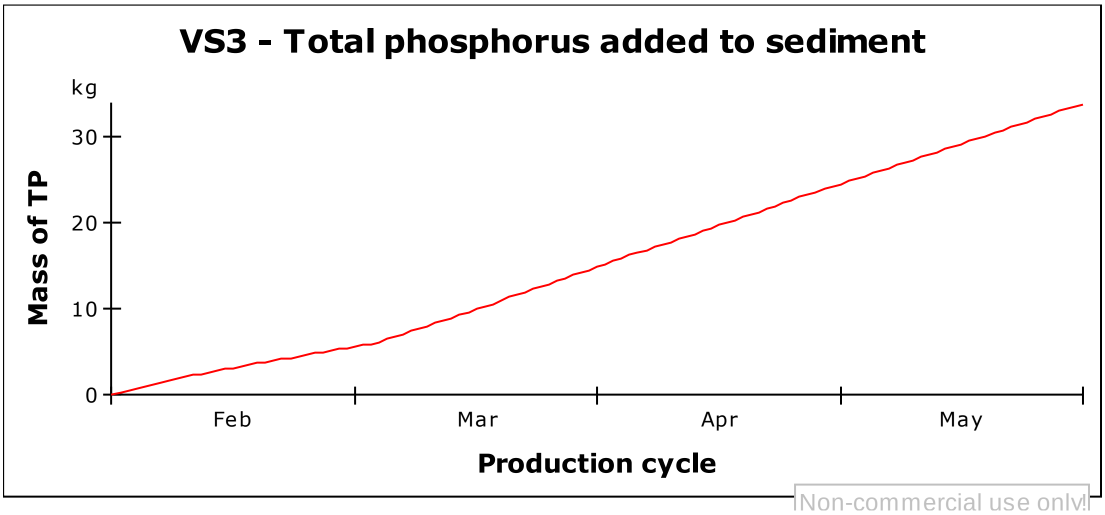



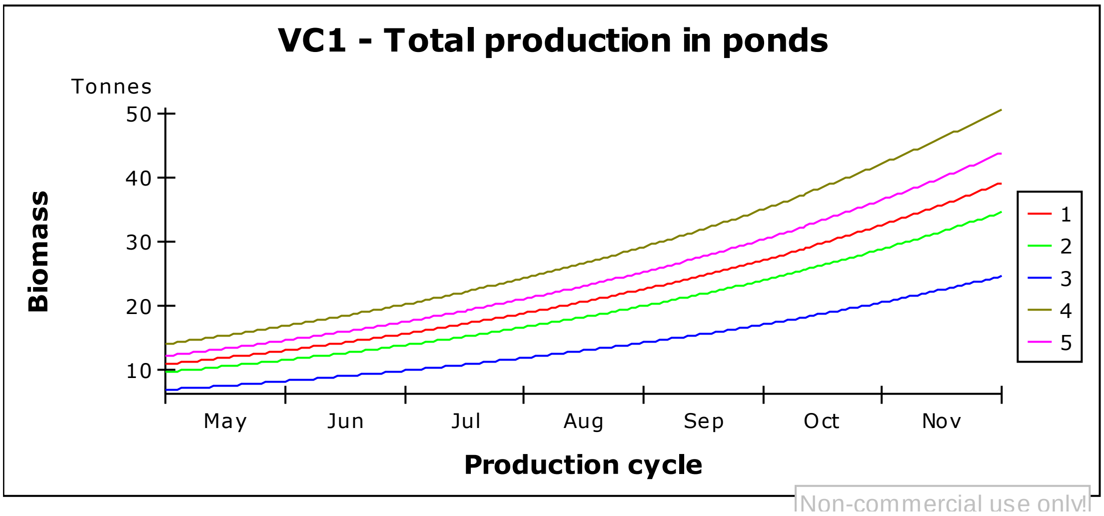

Figure 5.22: Model outputs for TP added to sediments for Vietnamese shrimp case study farms during the culture period (Powersim$^{TM}$ outputs)

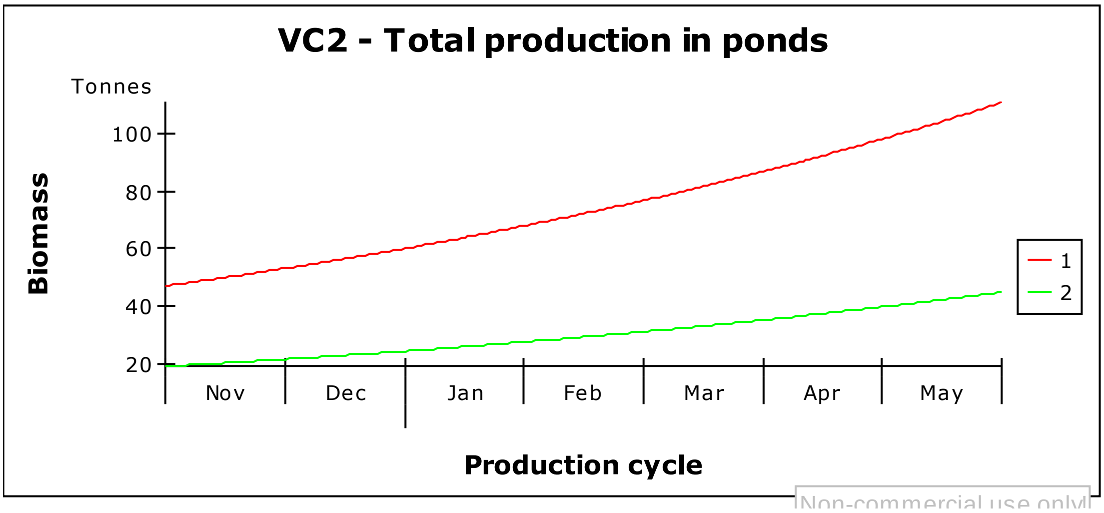
### 5.3.4. Vietnam catfish case study model outputs

#### 5.3.4.1 Total Production

Pangasius farming is intensive in its practices and produces high volumes of fish, which is reflected in the outputs of the production submodel results (fig. 5.23). VC1 returns a volume of 192.69 tonnes over 5 ponds, using a stocking density of 20 fish per $m^2$ and a recorded mortality rate of 22%. The maximum output for a pond at VC1 is 50.61 tonnes and a minimum of 24.57 tonnes.

VC2 (fig 5.23) produces 155.72 tonnes per cycle over 2 ponds with 110.78 tonnes in one and 44.96 tonnes in the other. Farm VC2 operates with a stocking density of 46 fish per $m^2$ with a 20% recorded mortality rate. The final farm, VC3, produces 221.54 tonnes over 3 ponds according to the outputs of the model. The maximum and minimum production numbers for the farm are 95.33 and 33.77 tonnes respectively, while operating with a stocking density of 30 fish per $m^2$ and a mortality rate of 25%.



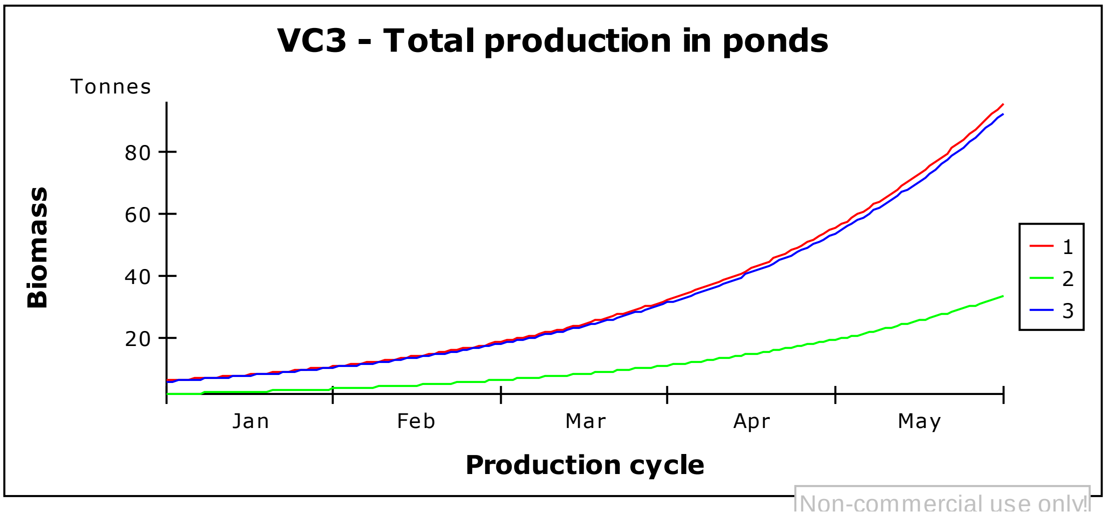




Figure 5.23: Total modelled production in three case study farms for Vietnamese catfish over a production period (VC1- 5 ponds; VC2- 2 ponds: VC3- 3 ponds) (Powersim$^{TM}$ output)

#### 5.3.4.2 Dissolved Oxygen

Pangasius farms have been known to have low DO level in the water due to the species being a facultative air breather. This results in the fish utilising the oxygen from the air when DO levels in the water are low. Farms VC1 and VC2 (fig 5.24) are indicative of the occurrence of low DO levels within the water, the mortality rate for each are around the 20% mark, supporting the theory that farmers do not have any major concerns over DO levels in the ponds. VC1 shows the level of DO in the pond water to jump dramatically at the end of August. There was a recorded increase in the DO level from 2.47 mg/l to 6.2 mg/l suggesting that the source water has a significant influence on the DO levels modelled in the farm. It should be noted however that there is a larger drop in DO levels from the end of August during water exchange event than in previous months when DO levels were less than 3mg/l.

VC2 shows a steady rate of DO within the ponds, with the exception of water exchange timings where the water is flushed out resulting in a lower volume of DO in the water overall.

VC3 in figure 5.24 remains above 5.5mg/l, only dropping to less than 4.0mg/l during water exchange activities, which is then increased again with the top up of water using source water. This farm does not utilise aerators, again suggesting that the source water DO has a large part to play in supporting the DO levels within the farm ponds.

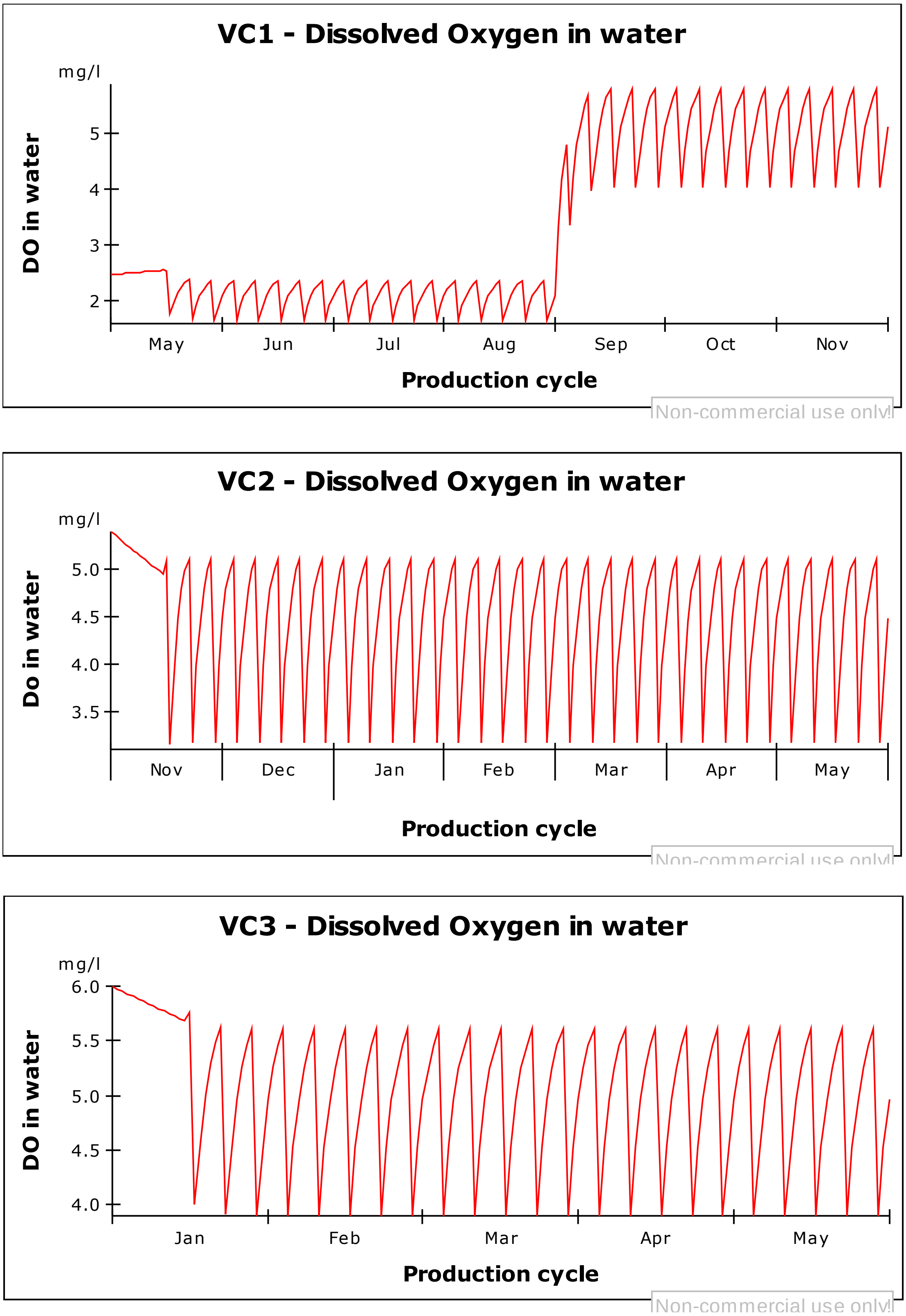



Figure 5.24: Model outputs for DO levels in pond water for catfish ponds used in Vietnamese case study farms during the culture period (Powersim$^{TM}$ outputs)

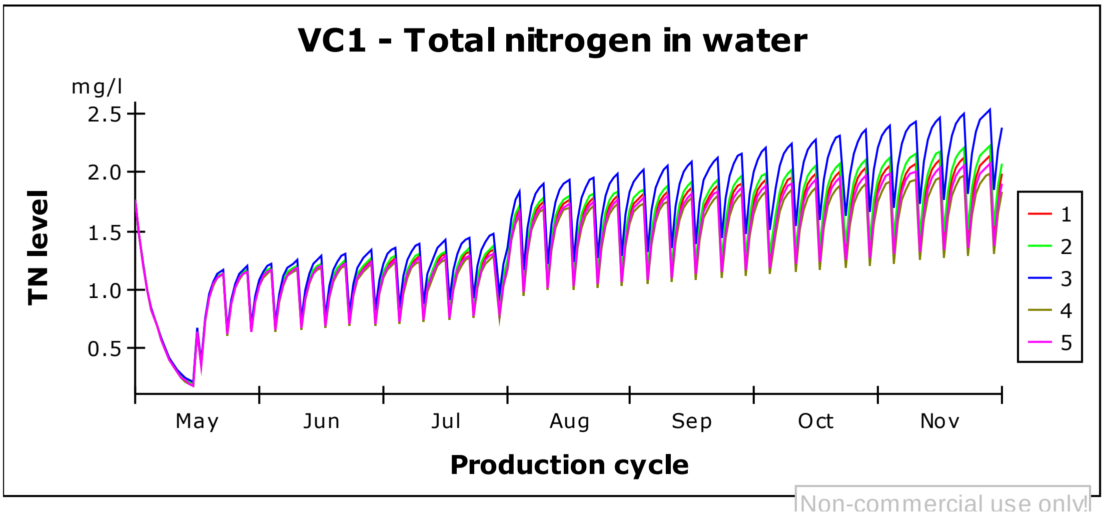
### 5.3.4.3 Total Nitrogen in water

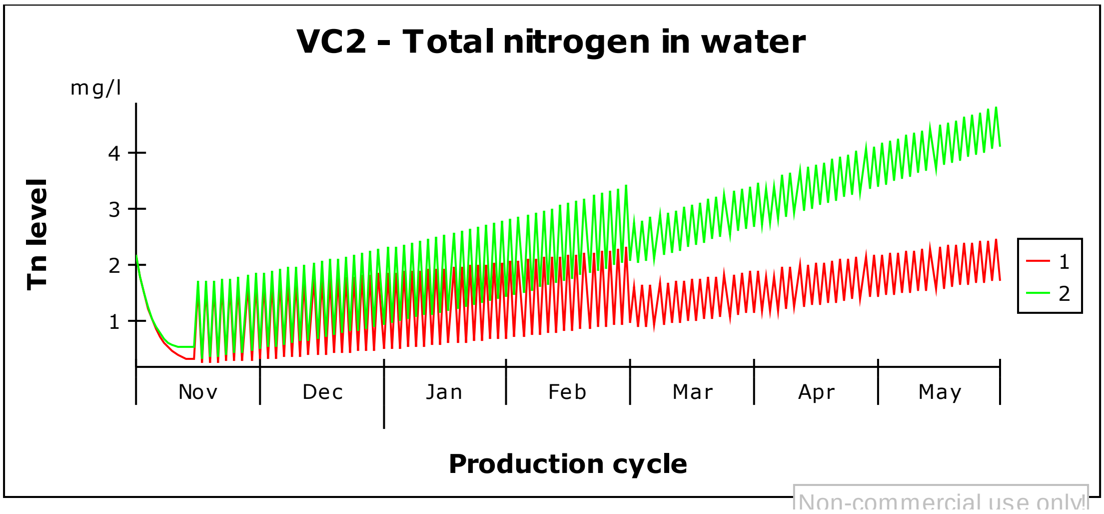
Pangasius farms are known to be highly intensive and therefore have a high level of inputs, it has been reported that feed and other inputs have been applied indiscriminately in order to maximise growth over a short period of time. Each farm shows and initial decrease in the TN level in the water in figure 5.25, except pond 2 in farm VC3

Farm VC1 shows an initial decrease in the modelled level of TP during the first 2 weeks of the production cycle from 1.77 mg/l to 0.18 mg/l. Due to the introduction of water exchange this increases to an average of 1.14 mg/l. The final average modelled TN level in the pond water is 1.7 mg/l with a maximum of 2.05 mg/l and a minimum of 1.49 mg/l. Although the model shows an overall trend of increase there is a clear definition between months one to three and the rest of the culture cycle. This is due to the increase in the recorded TN level in the source water used for water exchange at this point in the cycle from 1.77 mg/l to 2.38 mg/l.

Farm VC2 shows the same initial decrease as farm VC1, from 2.18 mg/l modelled TN to 0.44 mg/l. The ponds in farm VC2 both show an increase over the course of the production cycle of modelled TN, however pond 2 shows a higher increase (4.10 mg/l) than pond 1 (1.73 mg/l). This is possibly due to pond 2 being less than half the size of pond 1 at 3101 $m^2$ and 1259 $m^2$ resulting in less volume for the modelled TN to disperse over. Both ponds show a distinct decrease in the modelled level between months four and five. This is most likely due to the decrease in the recorded level of TN in feed from 4.11% to 3.02% as the source water used for water exchange was recorded to increase from 1.19 mg/l to 2.18 mg/l.

Farm VC3 again shows an initial decrease in the modelled TN level in the ponds from 1.67 mg/l to 0.35 mg/l for ponds 1 and 3 and 0.74 mg/l for pond 2. The farm shows a general increasing trend in modelled TN with an average final TN level of 2.67 mg/l between ponds 1 and 3 and a final modelled level of 6.10 mg/l for pond 2. This divergence can be attributed to the difference in pond size between the 3 ponds. Ponds 1 and 3 have an average water area of 3430 $m^2$ compared to pond 2 which has an area of 1234 $m^2$ resulting in less volume for the modelled TN to disperse over.



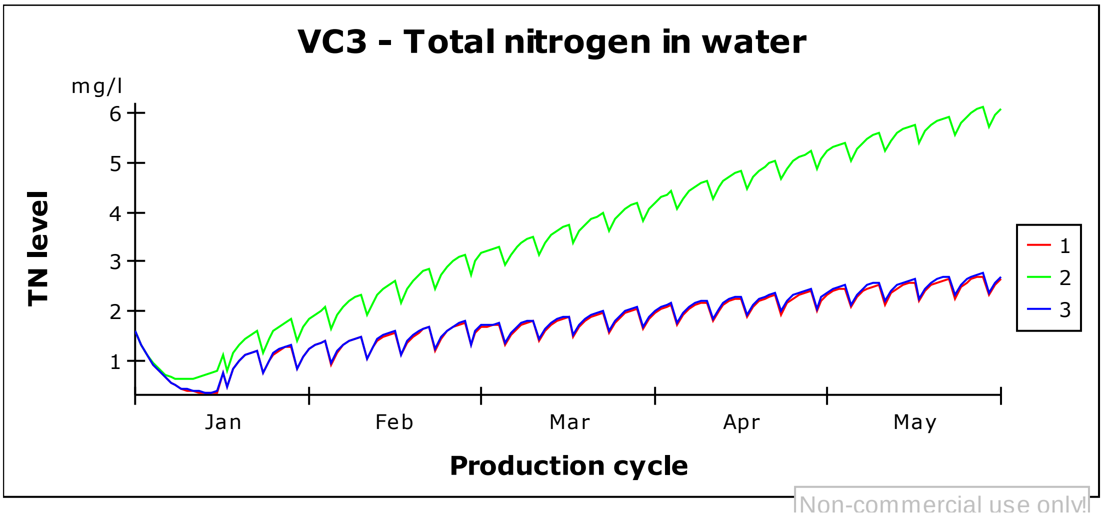
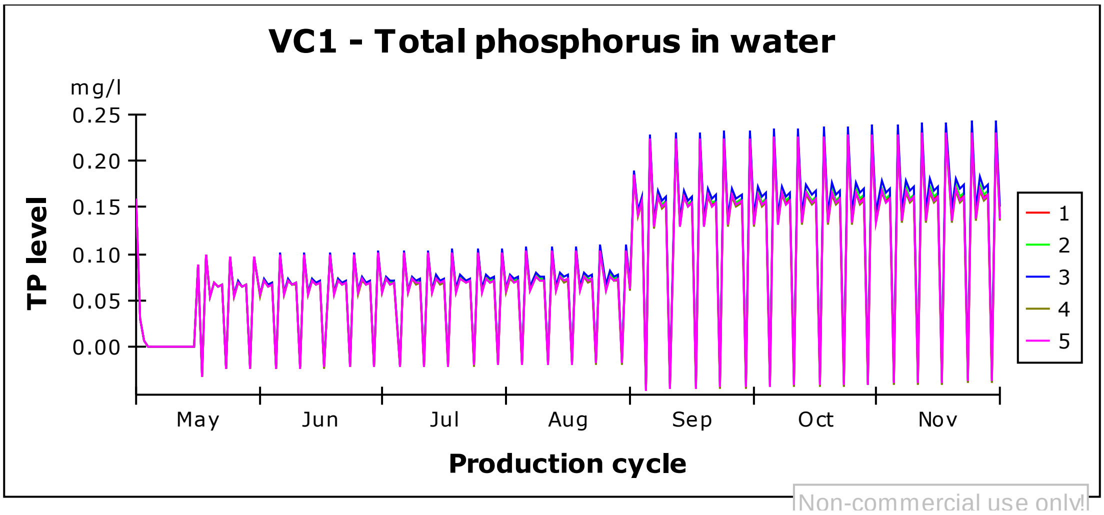



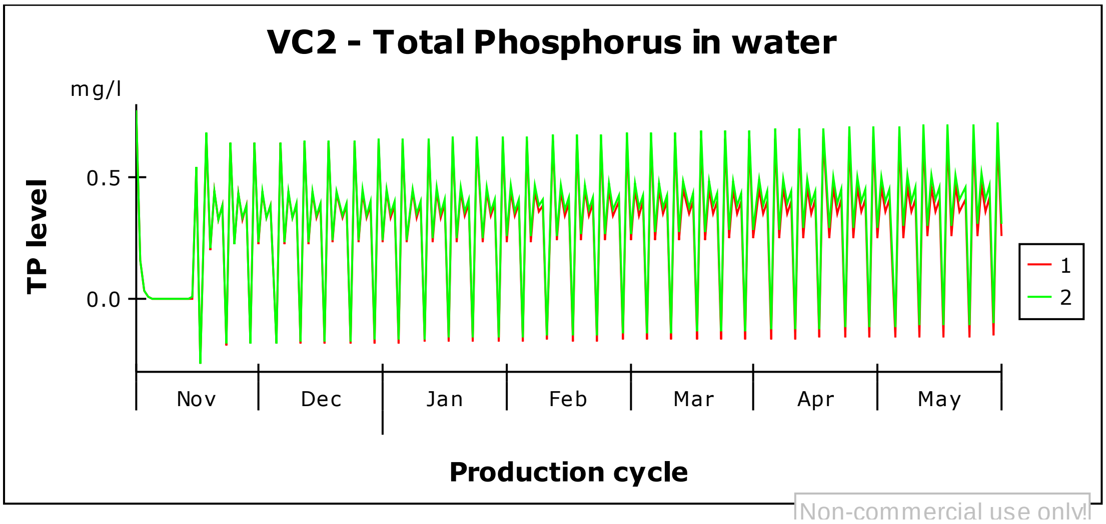

Figure 5.25: Model outputs for each Vietnamese catfish farm representing the total nitrogen in the water of each pond (Powersim$^{TM}$ output)

#### 5.3.4.4 Total Phosphorus in water

Modelled total phosphorus shows an increase over the course of the cycle for all farms (Fig 5.26). All farms show an initial decrease in the modelled levels of TP in the ponds followed by a spike due to the introduction of water exchange. Farm VC1 shows an initial decrease in the level of modelled TP in the water to 0.0007 mg/l. this then increases to 0.08 mg/l with the introduction of water exchange. The ponds show an increase in modelled TP over the course of the cycle with a final modelled average value of 0.14 mg/l TP with a maximum of 0.15 mg/l and a minimum of 0.14 mg/l. Throughout the cycle there is a clear definition point due to the change in the recorded TP in the source water used for water exchange from 0.16 mg/l to 0.36 mg/l.

Farm VC2 shows a relatively steady level of modelled TP in the ponds. The introduction of source water during water exchange causes a spike in the results which settles down within the day. The ponds return an average of 0.28 mg/l with a minimum of 0.26 mg/l and maximum of 0.31 mg/l. The recorded TP in the source water did not change significantly over the course of the cycle (0.77 mg/l to 0.78 mg/l),resulting in no obvious definition in the modelled TP levels. Farm VC3 also showed the initial drop in modelled TP levels in the first month until the introduction of water exchange where an increase of 0.039 mg/l occurs. The farm shows a steady rate of increase over all ponds with pond 2 returning the highest rate of increase. The final modelled levels are 0.06 mg/l, 0.10 mg/l and 0.06 mg/l for ponds 1, 2 and 3 respectively. As mentioned previously the higher level of modelled TP in pond 2 may relate to the size of the pond as the volume contained in the water has a smaller volume to disperse over resulting in a more concentrated level of TP.



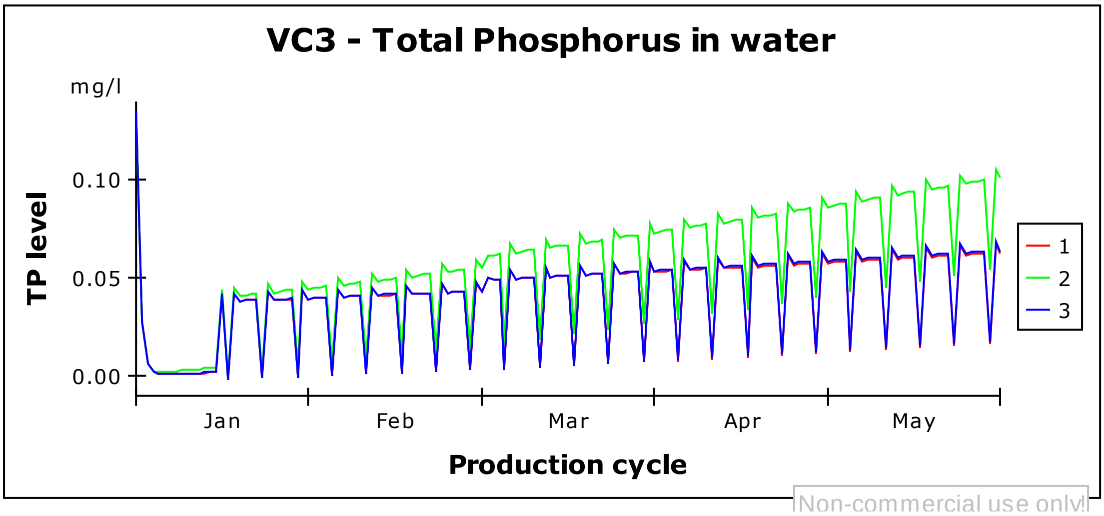
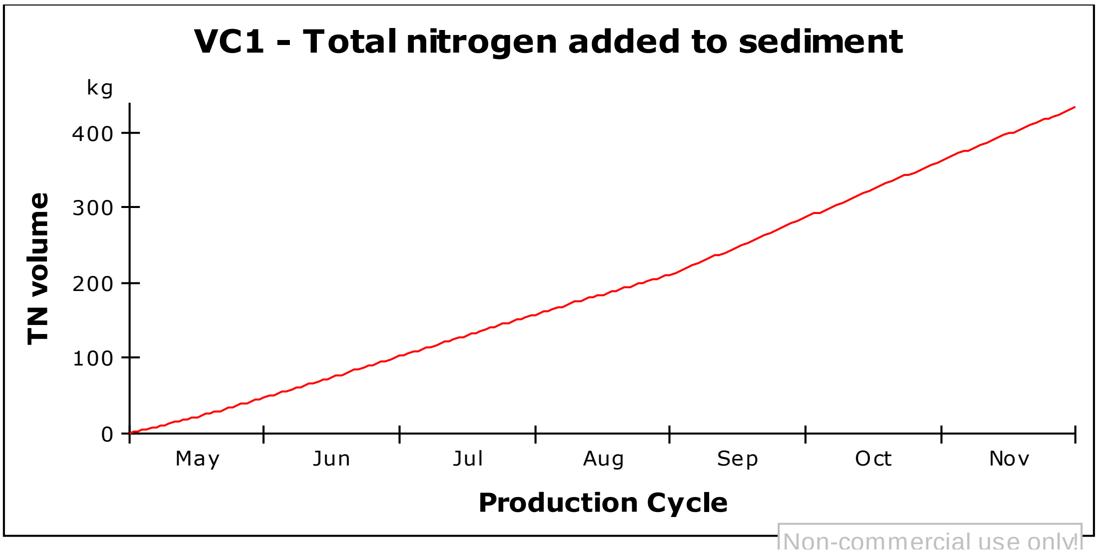



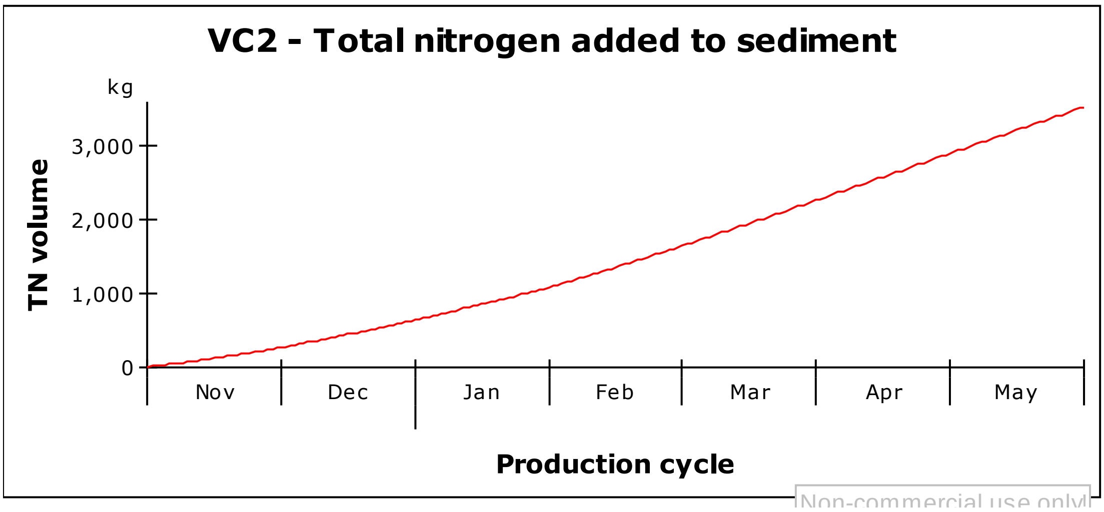

Figure 5.26: Model outputs for TP levels in each pond in the Vietnamese catfish farms (Powersim$^{TM}$ output)

#### 5.3.4.5 Total Nitrogen in sediments

Modelled total nitrogen levels added to sediments in the farms increase over the course of the cycle according to the Powersim outputs below (fig. 5.27). Farm VC1 shows a total modelled addition of 432.79 kg TN to sediments in the farm. This results in an input of 53.861 g/m$^2$. The rate of addition remains steady until the beginning of month five where an increase is observed in the rate. This is due to the increase in the recorded TN for both feed and source water from 3.04% to 4.82% (feed) and 1.77 mg/l to 2.38 mg/l (source water) Farm VC2 returns a modelled value of 3537.20 kg of modelled TN to the sediment equating to an input of 811.29 g/m$^2$. The rate of additions increases after the first 3 months of culture, although it is not as obvious as in farm VC1. This is due to the recorded level of TN in feed increasing from 3.02% to 4.11%, whereas the recorded water TN level showed a decrease from 2.18 mg/l to 1.19 mg/l. Farm VC3 shows the total modelled amount added to the sediment to be 2634.43 kg resulting in inputs of 325.42 g/m$^2$ to the system. There is a very small change in the rate of addition of modelled TN to the sediment after the second month of culture. This is due to the decrease in both the recorded feed TN content (4.58 % to 3.45%) and recorded TN in the water source (1.60 mg/l to 1.35 mg/l).

These results suggest that TN levels in feed have the biggest effect on the TN levels in the sediment as the farms which were recorded to have an increase in the TN content of feed over the course of the cycle showed an increase rate of modelled TN additions to the sediment, however farm VC2 also showed an increase in the rate of addition even though the recorded water TN content reduced over the course of the cycle.



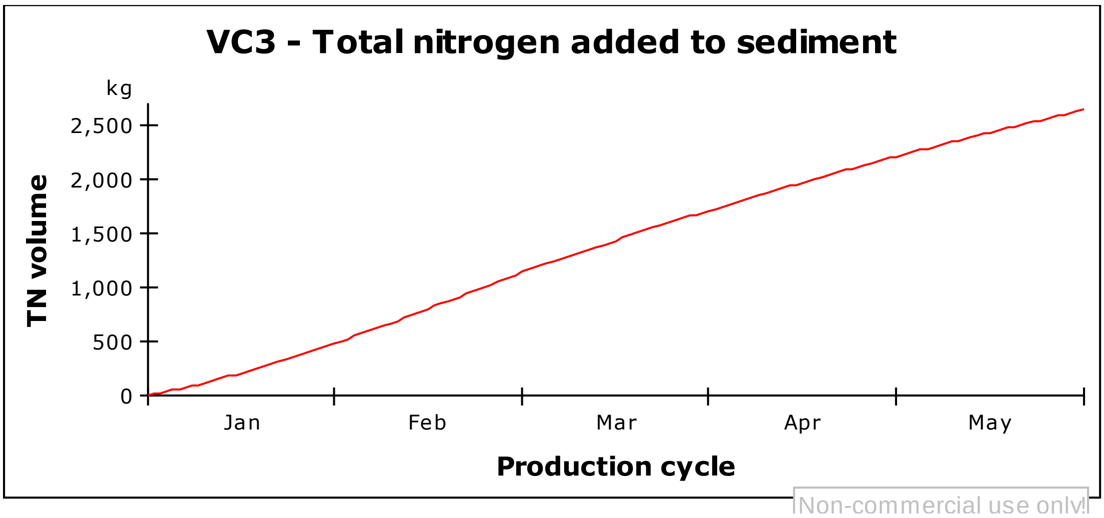




Figure 5.27: Model outputs for TP levels in each pond in the Vietnamese catfish farms (Powersim$^{TM}$ output)

#### 5.2.4.6 Total Phosphorus in sediment

As with the total nitrogen to sediment model, total phosphorus added to the sediment was modelled as the total for the farm as a whole to understand the level of accumulation in this sink for the three case study farms (fig. 5.28). Modelled total phosphorus added to the sediment, for farm VC1 was 637.23 kg P. This results in an input of 79.3 g/m$^2$. The modelled TP to the sediment shows a similar trend to the modelled TN added to the sediment for this farm with an increase in the rate of addition after four months, indicated by a steeper incline in the last three months. This is due to the increase in the recorded TP level in the source water (0.16 mg/l to 0.36 mg/l) as the increase of TP in the feed is small (0.7%).

Farm VC2 shows the modelled addition of TP to the sediment at 1225.45 kg TP resulting in an input of 281.07 g/m$^2$. The first 15 days shows a small addition to the sediment (42 kg) in comparison with the rest of the cycle, possibly from the introduction of water exchange though it is not clear.

Farm VC3 returns a modelled result of 709.36 kg TP added to the sediment with an input of 87.62 g/m$^2$. The model shows a very small change in the rate of addition to the sediment after the second month, most likely due to the increase in the recorded source water used for water exchange from 0.13 mg/l to 0.16 mg/l as the recorded feed TP content only differs by 0.1%. T

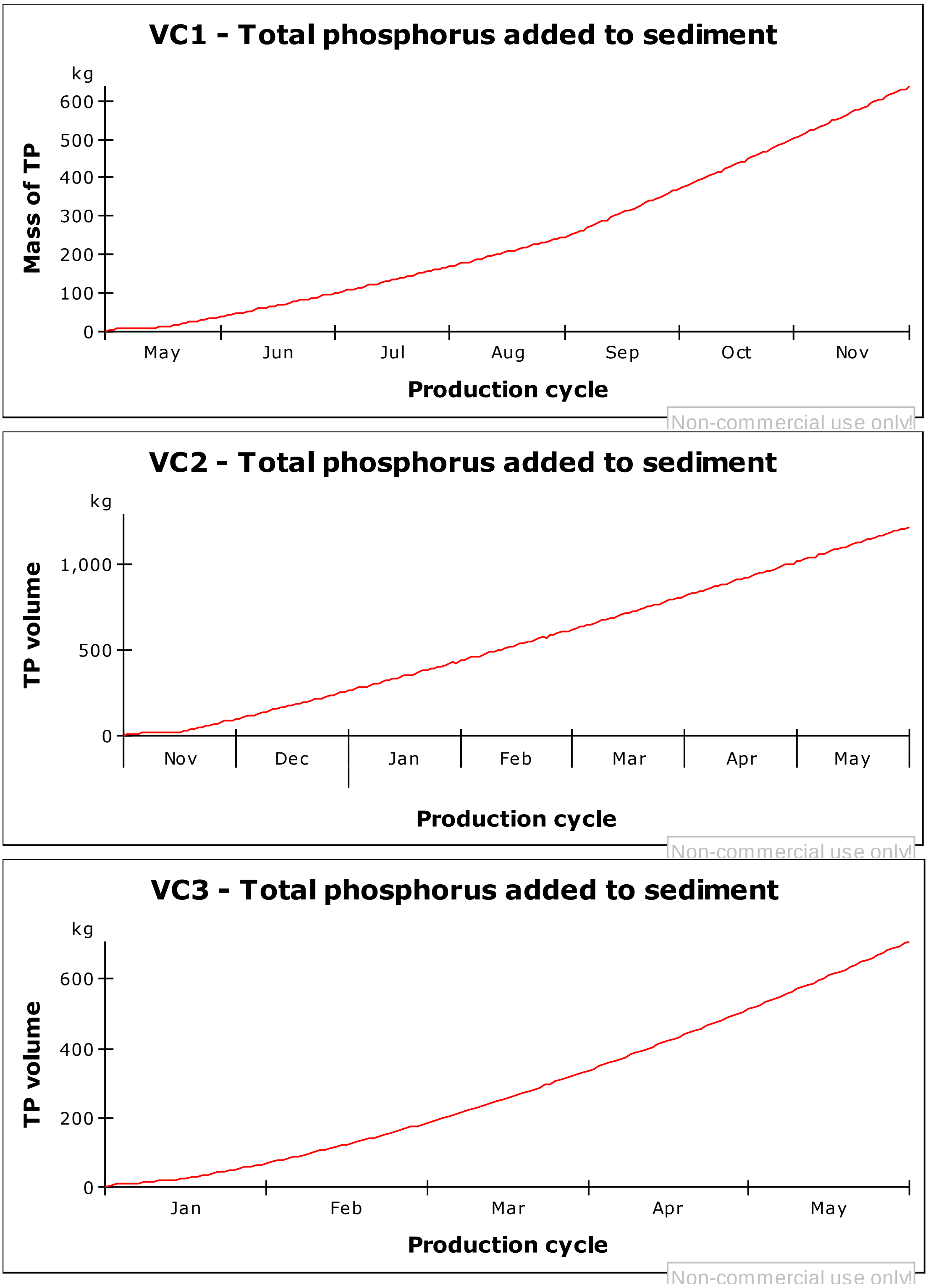



Figure 5.28: Model outputs for TP added to sediments for Vietnamese catfish case study farms during the culture period (Powersim$^{TM}$ outputs)

## 5.4. Discussion

The use of modelling to determine the effects of various farm management practices is a practical way of providing outputs for many farms, while reducing the requirement of time consuming data collection. The results outlined previously show outputs for the individual ponds in each farm case study. The models were designed as individual pond level models (see chapter 3) which were then combined as appropriate to account for all ponds within each farming system, with adjustments made to compensate for differences in farming practices between each pond. Figure 3.3 shows the major contributors to the model and how each section interacts within the model construction, with the model in full shown in Appendix 2. Having built the models in this way has allowed a holistic view of the effects of the farming practices on the individual ponds which can then be extrapolated to the impact the farm may have overall on the environment. For example case study TS3 contains 8 ponds resulting in the model being run 8 times with 8 different sets of parameters which can be combined to indicate the output of the farm as a whole. Many studies focus on a single pond in a farm and conclude an impact based on the single pond, however in practice each pond is a different size and will therefore hold different numbers of species. This can potentially result in differences in the impacts of each pond as an individual, which in this case has been accounted for and included in the model.

The results from the model outputs above indicate that increase stocking densities lead to increased levels of TN in the water column. The outputs for Thai shrimp indicate that the farm with the lowest stocking density returned the least TP and TN in the water though the highest levels in the sediments. This is most likely due to resuspension of nutrient from soils being related to the biomass. Shrimp have a tendency to burrow in pond sediments, a lower biomass in the ponds would result in less disturbance of the sediment. This is confirmed by the occurrence of the highest level of TN and TP modelled in the farm with the highest stocking density and the lowest values recorded in the sediment. Thai tilapia farms follows a similar trend in that the highest stocking density returns the highest levels of TN and TP in the water and TP in sediments. This is due to the higher level of inputs to the system in terms of feed and thus TP in feed. The model reports resuspension as a function of biomass, in accordance with Avnimelech *et al*. (1999), and therefore the highest biomass results in more mixing in the water/sediment interface. As nitrogen is readily resuspended, it is collected in the water, where the highest levels are reported. The lowest Stocking density returns the second highest addition of TP to the sediment. This is possibly due to there being fewer individuals to disturb the sediment in turn releasing less TP from sediments back to the water column. The same farm also shows the highest level of DO in ponds, suggesting that lower stocking densities are potentially a way of improving water quality in Aquaculture Farms in Thailand.

Shrimp farms in Vietnam also show the trend of higher stocking densities result in poorer water quality, with the lowest stocking density returning the lowest TN and TP levels in both water and sediment and the highest DO levels. Pangasius farms in Vietnam do not follow this trend. The model outputs show that the higher the level of final production the poorer the water quality. This may be due to reports of indiscriminate application of feeds still occurring within the sector. However the farm with the lowest stocking density also produces the second largest biomass and yet is returning the lowest values for TN in water and TN and TP in sediments. This is likely in part due to the use of aeration in the farm, increasing the DO level and thus improving the productivity within the system. Previous studies have investigated the water quality of aquaculture farms in SE Asia. Lorenzen *et al*., (1997) devised a model for the effect of farming intensity and water management on nitrogen dynamics in Thai commercial shrimp ponds. The model outputs represented the levels of TAN and NO in the water of a pond. The results suggested that over the course of a cycle the levels of the two compounds showed an increasing trend , but that the lowest levels of TAN and NO were found in farms with no water exchange. However it was found that the effect of water exchange depended highly on the stocking density within the farms, as the higher stocking densities result in higher TAN and NO levels in the study. The models shown above display some similarity to this study as the higher rates of stocking density are shown to have higher levels of nutrients in the water and sediment. It does however have some reliance on the water exchange rates as some of the farms display much higher water exchange rates than the others resulting in the introduction of nutrients from the source water (Farm VS3). Another study conducted, this time on fish ponds (Li and Yakupitiyage, 2003) suggested that TN and TP levels in tilapia ponds are driven by the addition of fertilisers. This coincide with the results shown above for tilapia, as the farm which shows fertilisation also returns the highest additions of TN and TP to the water and sediments. Although the trend is similar to this study it is not definitive proof that the reason farm TT1 has higher TN and TP in the water and sediment is due to fertilisation, though it will be a contributing factor. The same study also reports a decline in DO concentrations in water over the course of a cycle, which is displayed in all the models above, What Li and Yakupitiyage (2003) do not comment on, is the effect of water exchange on the DO levels. The variation seen in their models is the result of the action of fish respiration and heterotrophic decomposition. Anh *et al*. (2010) suggested that for 1 tonne of pangasius 1.5 kg TN and 0.8 kg TP result in loadings from waste water and sediment. The models produced for pangasius here exceed these figures, producing much higher quantities of TN and TP overall. The consultancy company Longline Environment (2014), have developed some aquaculture models, one of which is called POND (Franco *et al*., 2006). This is an onshore aquaculture model developed for water quality, effluent quality and general stress on production. The model is currently valid for two shrimp species (*Litopenaeus vannamei* and *Fenneropeneasu indicus*) and Oysters. It is currently under testing for the finfish *Oreochromis niloticus* and the shrimp species *Penaeus monodon.*

Nitrogen and phosphorus ratios are important in controlling the productivity of aquatic systems. Finding the right balance is important to prevent the formation of harmful algal blooms in the aquaculture systems. The Redfield ratio is a widely accepted finding that a N:P ratio of 16:1 results in the right balance for high productivity in a system (Gilbert and Burkholder, 2011). The models in this study suggest the case study farm ponds have high N:P ratio of over 100:1 in most cases. This results in high N loadings to the surrounding environment, which may have a higher TP content than the farms potentially resulting in blooms of cyanobacteria making the water unsafe for the species in the water and any human activity.

The case studies outlined in this chapter show similar trends to the previous studies outlined. This suggests that the relationships created through the model reflect work carried out for similar species. The models presented may be used to indicate the dynamics of TN and TP in water and sediment and DO in water, which can also enable the user to work out the N:P ratio within the farm to help determine the impact the farm is having on the surrounding environment. If a group of farmers monitor their effluent quality within an area it is possible that, through mitigation efforts, the public water bodies may improve in quality also, benefiting not only local stakeholders but the local aquaculture ventures also.

# CHAPTER 6

# MODEL VALIDATION

## 6.1. Introduction

Model validation is an important step which can determine whether a model does in fact reflect the system it is designed to simulate (Bellocchi et al., 2010). Ford (2010) makes an important observation with regards to validation:

*"The key to a models usefulness is leaving out the unimportant factors and capturing the interactions between the important factors."*

Many models are very specific and attempt to include all interactions within the study boundary, which although may give a more robust model, will only apply to the specific system modelled (Wainwright and Mulligan, 2013). In the models produced for this study the whole farm was set as the boundary and therefore the most important factors were concluded to be the inputs of TN and TP through feed, fertiliser and other sources vs the water management practices applied to the farm, such as water exchange rates.. The model scale meant that every tiny interaction between phytoplankton and the various forms of nitrogen were not included, nor the night time interactions which have been known to affect DO levels. Ford (2010) goes on to suggest that the removal of specific variable or interactions within a model, leave it subject to criticism, however points out:

*"Such criticism is pointless. It reveals the critic does not understand the nature of modelling."*

This statement can be fully understood by the explanation that a model is the simulation of the processes within a system and not a replication of the system itself thus does not require every single interaction to be represented. The inclusion of every interaction within the farm level boundary would cause the model to become cumbersome and difficult to track any issues that may need readdressing throughout the modelling process (Wainwright and Mulligan, 2013).

Validation of models occur throughout the modelling process (Barlas, 1994), the most common being direct structure tests comparing process equations with previous studies in literature. Final validation involves testing the behaviour of the model to determine the overall usefulness of the output.

## 6.2 Validation methodology

Validation was derived from the behaviour of the model as a test of fitness to the system. Data was gathered from farms at various points in the year as agreed with farmers. On the whole 4 sampling points were agreed to with Thai farmers. Vietnamese farmers allowed 2 sampling points. One at the start of the cycle and one at the end of the cycle. Data was not collected at every sampling point for all the farms due to the farmers denying access to the ponds (table 5.2; chapter 5). This indicates there is still some distrust of aquaculture farmers to outside studies. Data for TN, TP and DO were collected for water, feed and sediment. Using a large integrated farm survey applied by the SEAT project, data for production was also provided.

A paired t test was used to determine the variance between the observed data compared to the modelled data. This allows a statistical difference to be determined between the data collected and that which is simulated. In order to provide a small back up to the validation the model accumulations are also included and compared to the literature to provide a level of verification to the models.

## 6.3 Case studies vs collected data

Comparisons of the data collected (Chapter 5) versus the modelled results were made in order to determine if the models could be verified. Water samples were taken from each case study farm in each country and analysed for TN, TP and DO. The samples were taken at specific points during the cycle, therefore the models were run to the corresponding points with the sampled results and the values taken (table 6.1 and 6.2). A t-test was then used on the two sets of data for each parameter to determine whether there was any significant difference between the collected data and the modelled data in the same point in time of the production cycle. Tables 6.3 and 6.4 show the results of the t test carried out for the sets of data and also show an indication of whether the submodel have been verified by the presence of a check (verified) or a cross (unverified).

**Table 6.1 :Results of the t-test carried out on fish ponds for verification of the models (Kleijnen, 1995)**

| **Thailand** | | | **Vietnam** | | |
|---|---|---|---|---|---|
| TT1 | One tail t | verified | VC1 | One tail t | verified |
| DO | p>0.05 | × | DO | p>0.05 | × |
| TN in water | p<0.05 | ✓ | TN in water | p>0.05 | × |
| TP in water | p<0.05 | ✓ | TP in water | p>0.05 | × |
| TT2 | | | VC2 | | |
| DO | p>0.05 | × | DO | p>0.05 | × |
| TN in water | p>0.05 | × | TN in water | p>0.05 | × |
| TP in water | p>0.05 | × | TP in water | p>0.05 | × |
| TT3 | | | VC3 | | |
| DO | p>0.05 | × | DO | p>0.05 | × |
| TN in water | p>0.05 | × | TN in water | p>0.05 | × |
| TP in water | p>0.05 | × | TP in water | p>0.05 | × |

**Table 6.2: Results of the t-test carried out on shrimp ponds for the verification of the water quality model (Kleijnen, 1995)**

| **Thailand** | | | **Vietnam** | | |
|---|---|---|---|---|---|
| TS1 | One tail t | verified | VS1 | One tail t | verified |
| DO | p<0.05 | ✓ | DO | p<0.05 | ✓ |
| TN in water | p>0.05 | × | TN in water | p>0.05 | × |
| TP in water | p>0.05 | × | TP in water | p>0.05 | × |
| TS2 | | | VS2 | | |
| DO | p<0.05 | ✓ | DO | p<0.05 | ✓ |
| TN in water | p<0.05 | ✓ | TN in water | p>0.05 | × |
| TP in water | p<0.05 | ✓ | TP in water | p>0.05 | × |
| TS3 | | | VS3 | | |
| DO | p>0.05 | × | DO | p>0.05 | × |
| TN in water | p<0.05 | ✓ | TN in water | p>0.05 | × |
| TP in water | p>0.05 | × | TP in water | p>0.05 | × |

The results of validation vary with some of the submodels accepted as valid. An explanation for the variation is simply the limited number of sample points allowed by farmers. It is possible that with a continuous sample collection with a larger number of sample points that there would be more cohesion between the models and the data points. This was indicated in the results of the t tests where the p value is above 0.05. In some of the cases the p value exceeds the α value by 0.02, indicating the possibility that with further data points there may be some more cohesion between the data and the model.  It also would allow for better input data. Some farms saw a large fluctuation in the quality of the source water, which would be better explained with a larger data set. However it should be pointed out that the farmers selected for further sample collection permitted only the sample points given. This was particularly the case with shrimp farmers in both countries. Shrimp farmers are sensitive to studies due to previous poor press and disease outbreaks with a major disease event occurring in the Mekong Delta approximately a year previously (FAO, 2013). Both tables 6.2 and 6.3 show the effect of the different number of sample points as there is much less verification of the modules in Vietnamese farms than that of the Thai farms. Due to the low level of data acquired from the farms a literature comparison of accumulations was used to investigate the percentage of nutrients collected in each of the sinks identified.

## 6.4. Accumulations in fish ponds

The source of TN and TP in fishponds varies with species. The case study farms show feed to be the main source of both nutrients. However tilapia farms have an average of 54% of TN and 36% TP coming from feed added followed by nutrients introduced through supply water and water exchange activities at 44.66% TN and 36% TP. Pangasius farms show an addition of over 80% TN from feeds, for farms VC2 and VC3 and 54% for VC1, and between 40 and 50% TP.

Nutrients accumulate in various locations within the production system. These locations are known as sinks and are identified as the harvest species, sediments, the pond water, the environment (from water exchange events) and in this case the breakdown of TN. Although TN does not accumulate in this Break Down “sink” it is a set of actions which utilises the nutrient reducing its presence in other sinks therefore resulting in its inclusion to fully comprehend the accumulation factors. Table 6. shows the accumulation of TN and TP in various identified sinks in the system for tilapia and catfish. It is evident in both species that the fish take up most of the TN put into the system, with the exception of TT2 where much of the TN is flushed out to the environment throughout the production cycle. The second most important sink is the environment. With water exchange occurring throughout the cycle, TN is released as a percentage of the level recorded in the ponds at the time of release. TP accumulations in sediments are important in both species. The tilapia case studies appear to show the highest accumulation rates at 93.33% and 82.52% for TT1 and TT2 though TT3 only accumulates 27.42%. Pangasius farms accumulate less though still accounts for nearly half of the TP added to the system at a range of 44.44% to 48.78%. The level of TN and TP left in the farm water at harvest depends on the level of water exchange utilised on the farm. High levels of water exchange reduce the level of nutrients left in the farm at the end of the cycle.

**Table 6.3: Percentage (%) of TN and TP accumulated in each sink identified in fish ponds**

**Total Nitrogen**

| Sink | TT1 | TT2 | TT3 | VC1 | VC2 | VC3 |
|---|---|---|---|---|---|---|
| Fish | 41.22 | 14.90 | 33.61 | 33.24 | 51.21 | 52.19 |
| Sediment | 24.35 | 4.88 | 5.60 | 6.83 | 19.78 | 0.43 |
| water | 8.45 | 21.72 | 24.32 | 0.81 | 0.21 | 0.97 |
| environment | 25.01 | 53.21 | 33.23 | 36.86 | 22.89 | 28.82 |
| Broken down | 0.98 | 5.29 | 3.23 | 22.26 | 5.92 | 17.59 |
| Total | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

**Total Phosphorus**

| Sink | TT1 | TT2 | TT3 | VC1 | VC2 | VC3 |
|---|---|---|---|---|---|---|
| Fish | 3.94 | 16.69 | 44.87 | 28.84 | 23.99 | 50.60 |
| Sediment | 93.33 | 82.52 | 27.42 | 48.78 | 46.47 | 44.44 |
| water | 0.57 | 0.36 | 9.16 | 0.29 | 0.18 | 0.16 |
| environment | 2.17 | 0.42 | 18.58 | 22.09 | 29.36 | 4.52 |
| Total | 100.01 | 99.99 | 100.03 | 100.00 | 100.00 | 99.72 |

## 6.5. Accumulations in shrimp ponds

The nutrient inputs for shrimp ponds came mainly from feed and fertilisers if they are used (table 6.4) . In the case studies over 90% of the TN and 70% for TP additions come from feed added to the system. The exception to this is TS3 where only 43% TP comes from feed and 55% is added through the use of fertiliser and VS3 where nutrients are added through the use of fertilisers and water exchange resulting in 74% TN and 1.34% TP added through feed. As with the fish pond results the harvested shrimp are the highest sink for TN in the system with approximately half accumulating at an average of 55.11 % for TS farms and 49.19% for VS farms. However the sediment is shown to take approximately half of the TP in the system. This is likely due to its affinity to bind with the pond soils. Much of the remaining TN is either broken down or accumulated in the sediment with a small percentage actually entering the environment with the exception of VS3. TP accumulates almost equally over two sinks; the species and the sediment (table 6.4). the third farm for each country shows exception to this. TS3 has a 73.55 % accumulation in sediment with only a 25.45 % accumulation in the species. VS3 indicates that the accumulation of TP occurs between the sediment (34.99%) and the environment (60.55%). This is likely due to the low water exchange rates within the systems therefore causing both the TN and TP to become tied up in the production system.

**Table 6.4: Percentage of TN and TP accumulated in each sink identified in shrimp ponds**

**Total Nitrogen**

| **Sink** | **TS1** | **TS2** | **TS3** | **VS1** | **VS2** | **VS3** |
|---|---|---|---|---|---|---|
| Fish | 53.60 | 58.49 | 53.34 | 51.46 | 53.22 | 42.90 |
| Sediment | 32.79 | 33.47 | 2.37 | 30.29 | 29.41 | 29.50 |
| water | 1.12 | 0.48 | 3.19 | 1.28 | 1.25 | 0.80 |
| environment | 0.83 | 0.08 | 0.47 | 0.92 | 0.66 | 13.46 |
| Broken down | 11.66 | 7.18 | 41.14 | 17.45 | 15.46 | 13.34 |
| Total | 100.00 | 99.69 | 100.51 | 101.40 | 100.01 | 100.00 |

**Total Phosphorus**

| **Sink** | **TS1** | **TS2** | **TS3** | **VS1** | **VS2** | **VS3** |
|---|---|---|---|---|---|---|
| Fish | 57.43 | 35.04 | 25.45 | 51.21 | 47.70 | 0.79 |
| Sediment | 42.25 | 64.10 | 73.55 | 48.49 | 51.83 | 34.99 |
| water | 0.16 | 0.68 | 1.00 | 0.11 | 0.12 | 3.67 |
| environment | 0.13 | 0.18 | 0 | 0.11 | 0.07 | 60.55 |
| Total | 99.83 | 100.00 | 100.00 | 99.93 | 99.72 | 100.00 |

## 6.6 Discussion

Validation of a large complex model can be difficult as shown in the validation results above. While a model may conform to expectations it may not replicate the system using time series data as there are other external forces applying pressure on a system which may not be accounted for in a model (Taylor, 1983). The most obvious point raised in the validation section is that a stronger dataset may be required for validation of system dynamics models. This is indicated in the difference in the Thai model validation compared to the Vietnamese model validation. It is clearly not possible to achieve significant validation using only 2 data points, while 4 data points are able to some extent to provide an indication of the parameter measurements at a given season. The accumulation results provide some interesting insights into the percentage of nutrients collected in each of the identified sinks in the production systems. Historically N and P added from feeds were recorded to collect on the pond bottom (Avnimelech and Lacher, 1979). However with advances in the understanding of how to develop more efficient feeds that number has been reduced resulting in greater retention of nutrients by the culture species. While the volume has been reduced it is still the case that the greatest additions of N and P come from the feed (Rafiee and Saad, 2005). The models have shown that the largest sink for nutrients, particularly TN is the production species. This is possible due to improved feed recipes and a better understanding of feeding versus growth in production systems. It is thought that very little of the feed is now wasted in many systems. TP results reflect the view that the sediments in closed production systems are the main sink for the nutrient due to their affinity for binding with muds in comparison to their solubility in the water.

# CHAPTER 7

# DISCUSSION

With an increasing population, food security is becoming increasingly important. It is reported that the global population is set to reach 9 billion by midway through the 21st century (Godfray *et al*., 2010a; Garcia and Rosenberg, 2010). With overexploitation of capture fishery stocks and increased competition over land use for food, cash crops and biofuels, increasing food demands can be met through the development of sustainable aquaculture (Godfray *et al*., 2010a; McClanahan *et al.,* 2013). One of the most notable attributes of the aquaculture sector is its rate of growth, with production outweighing that of capture fisheries in many regions (Godfray *et al.,* 2010b; FAO, 2010).

The expansion of the aquaculture industry is most prevalent in South East Asia, where the increase has been nearly 16 fold over 50 years, excluding China (FAO, 2010). This level of expansion has resulted in attention being drawn to the potential implications this has on the environment, thus resulting in many negative reports surfacing with regards to the production of aquatic products (Belton *et al.,* 2010; Little *et al*., 2012). This has motivated public policy makers to take steps towards initialising regulations with regards to the environment and working with international groups to develop sustainability guidelines on the levels of various parameters allowed to enter the environment from effluents (GlobalG.A.P., 2012; GAA, 2011)

In order to determine the level of impact a production system has on the environment, decision support tools can be utilised. Decision support tools come in different forms including spatial maps, allowing the user to determine land availability or non point sources of pollution (Falconer, 2014). Others are able to simulate the effect of specific practices on a system, as is the case with System Dynamics models.

System Dynamics models are a representation of a system, which simulate the effect a particular set of actions has on the study field (Ford, 2010). There are a variety of dynamic models available for use as decision supports tools (Jamu and Piedrahita, 2002b; Ferreira *et al*., 2007; Liu *et al.,* 2009) however these are applied to specific systems and require intricate datasets in order to function. For the application of models in South East Asia, over a wide ranging set of farms, it is important to keep data requirements simple as any farmers are still wary of providing information on production practices to outside sources.

## Site Selection

Site Selection is an important part of any study, regardless of the field. In recent years there has been a push towards the adoption of large research projects, utilising many areas of expertise in order to provide a holistic view of the system under scrutiny. While the implementation of the large integrated project may provide groundbreaking results, there are also likely to be a number of differing objectives required by various stakeholders that must be addressed (MEXT, 2012, Watts and Halliwell, 1996). The SEAT project is such a project, drawing expertise from social, commercial, food safety, ethical and environmental backgrounds (SEAT, 2012). All stakeholders within this project have different goals for research therefore a one size fits all site selection approach may have resulted in a "groupthink" situation thus losing important site selection factors required by a particular group (Kiker *et al*., 2005).

In a large project, such as SEAT, it is likely that an initial scoping study will be carried out, providing the overall sites that can be further studied in the project. In order to counteract any bias introduced in the initial selection process, be it simple location bias or otherwise, multicriteria analysis can be used to refocus further site selection with the resulting sites having more relevance to the study to be undertaken (Burton *et al*., 1991). Multivariate analysis provides an indication of the similarity between sites based on the conversion of pre-existing data to a binary format, removing any initial pre judgement on the dataset to be analysed. It should be noted that multivariate analysis is not completely unbiased as it involves selecting a dataset that is understood to have the greatest effect on the system studied. It simply removes any pre-existing bias on the selected dataset, essentially providing a clean slate for a comparison of the similarity of the sites.

## Dynamic models

Dynamic models are becoming more popular with decision makers and will continue to do so as the need for increased food production grows. As mentioned earlier, it is expected that the aquaculture industry will be required to fulfil a major role in providing global food security. In order to do so production systems will either have to expand or intensify, both of which will result in increased pressure on the environment (Bostock *et al*., 2010). Much of the aquaculture production in South East Asia is conducted in land in closed production systems (FAO, 2010). This has the potential to lead to a build up of nutrients combined with a reduction in DO, resulting in potential eutrophication events (Tucker and Hargreaves, 2012). While this is an issue for the farmer, due to the release of effluents to the surrounding water bodies, it is of major concern to other water users also. Farmers have the ability to mitigate against eutrophication action through water management practices such as improved FCRs and changes in water exchange practices (Glencross *et al*., 2007; Boyd and Zimmerman, 2010)

The use of dynamic models to address the effect that water management practices have on the water quality is potentially a tool that could be used to aid farmers in improving the sustainability of their farms not only reducing their effect on the environment but ensuring the longevity of the farm itself through improved growth rates and reduced mortalities.

The models constructed for this study set the boundary to be the entire farm, where many other models focus solely on a single pond resulting in a very specific model. These models fit very well to the system but may face issues when applied to another with different management strategies (Jamu and Piedrahita, 2002b; Jackson et al, 2001). The models developed in this study were shown to be effective early on as the outputs are shown to be within expected levels described in literature and do not vary wildly. Indicating that the development stage of the models resulted in effective outputs that can be applied to single ponds for either fish or shrimp aquaculture.

Further development of these models allowed the pond model to be adapted and expanded to include all ponds within a farming system. This results in a “jigsaw like” situation where the full impact of the farm is clearly seen through the results by providing separate outputs from the individual ponds. This is a more holistic approach to modelling than has been previously used. Many models of pond aquaculture focus primarily on a single pond and extrapolate the results to assume the overall impact of the farm. While the model developed here accounts for differences in sizes of ponds, number of species stocked in ponds and therefore affects the overall inputs to the ponds.

While 400 farms in each country were selected overall by the project the outcome of the multivariate analysis allowed farms with similar water management strategies to be identified, with models based on a randomly selected few, as representatives of the group. This method allows generalised models to be constructed and applied easily to other members of the same group as constructing over 800 farm models would be a cumbersome and time consuming job requiring a large amount of data.

## Fish models

The tilapia case study showed that higher stocking densities result in higher levels of both TN and TP in the water. However it indicates that there is a higher level of TP in the sediment. The higher level of TP in the sediment may be due to the high level of feed added combined with the additions of fertilisers to the system.

The pangasius case studies appear to result in the water quality depending on the final biomass produced and less so on the stocking density. However it should be noted that the models showed that decreasing stocking densitiy of pangasius results in an increased level of DO in the water. While it has been documented that pangasius is a facultative air breather an improved DO level will not only benefit the fish but reduce the impact of effluent on the environment.

The fish models all indicate that the water quality in the ponds rely on the quality of water that is introduced to the farms from the source. High levels of nutrients introduced from feed and fertilisers coupled with poor initial water quality lead, inevitably, to a higher possibility of eutrophication within the ponds. When the water quality improves the DO level in the ponds is also shown to increase while the level of TN decreases, which would be expected. Many fish farms lie in areas of high density aquaculture and essentially rely on each other to not pollute the water systems. The models indicate that an improvement in effluent quality may result in an improvement in water quality for whole groups of farms as the initial water supply quality may be increased thus reducing pressure on the semi-intensive to intensive systems.

## Shrimp models

The models indicate that higher stocking densities result in higher levels of TN in the water but lower levels of TN and TP in the sediment. This result can be explained by the fact that shrimp are natural burrowers and more individuals will result in more resuspension of nutrients from the sediment to the water. The higher TN level in the water may be a result of the resuspension of the nutrients from the sediment combined with a higher volume of feed addition to compensate for the higher number of individuals in a pond.

As with the fish models, the shrimp models also indicate that poor quality supply water has a negative effect on the production system, however shrimp systems are less affected by this due to their lower levels of water exchange. The shrimp farms do however rely on a good DO level in the source water as the models indicate an almost continuous drop in the DO level throughout the cycle almost reaching the lower limit set out by BAP guidelines (3mg/l) (GAA, 2011). Only one farm falls below this, however receives water with a DO level 0f 3.5mg/l. The other farms have higher initial DO level in the ponds and may not reach the critical limit due to the short term over which shrimp farming occurs.

## Validation

Validation of the models was not entirely possible in this instance due to the small number of sample points approved by the farmers. In a large project such as this permission for access can be a hidden constraint and in this case some farmers who may have agreed to further sampling changed their minds at a later date, as indicated in Chapter 5; table 5.2. It is possible that with further data collection the models would have the chance to not only be validated but also refined with further inputs. Many studies collect data at frequent intervals resulting in robust datasets. However in such a large study it is possible that the farmers may have suffered from sampling fatigue or possibly still have some trust issues with providing access to international groups.

It was, however, possible to compare the accumulations of nutrients in the various sinks in each system. Overall the models indicate the production species to be the main sink for TN and the sediments as the main sink for TP. Previous studies suggest that the main sink for TN and TP is the sediment (Verdegem, 2007) with the latter confirmed in the model, due to its affinity for binding with muds (Boyd and Tucker, 1998; Boyd, 1995). A possible reason for the main sink being the production species is the development of more efficient feeds resulting in better FCRs and nutrient utilisation.

## Improvements to the study

The study overall provides effective outputs for the models constructed, however there was clearly not enough data to effectively validate the models. This is possibly due to the lack of trust in outside studies by the aquaculture industry in South East Asia, which has seen much negative attention in the media. An indication of this is shown in the data collected (chapter 5) where some farmers denied access part way through the sampling schedule. A possible way round this would be to have someone who the farmer trusts take the samples which may result in a larger more consistent sample set than the one outlined in this study.

The model assumes the TN and TP content of specific fertiliser and the volume and frequency added, based on previous studies. Further information on the actual application would allow the model to more accurately simulate the effect of fertilisers on the water quality at the actual time it is added and not at an evenly distributed value. Information on the length of time aerators are used for could result in an improvement in the dissolved Oxygen model as it would allow the model to determine the actual additions of DO to the water from manual aeration. Samples taken at various times throughout the day would also improve the accuracy of the simulation as previous studies have shown there to be significant differences in the DO level in ponds throughout the course of a 24 hour period (Culberson and Piedrahita, 1996). While the models are not fully validated they do conform to previous studies and could be used in a support capacity. A decision need to be taken whether to retrospectively manage a problem that arises, in which case may have devastating consequences, or to apply the model to pro actively manage a farm to prevent eutrophication and possibly improve output of the production of the farm.

## Application of models to SEAT

The models produced in this study have been used as part of the development of an aquaculture product index. The SEAT project is currently fine tuning a new index called EAFI (Ethical Aquaculture Food Index). As part of this index, the effect of current aquaculture practices on the environment were considered and a Rapid Assessment Toolbox was developed. The toolbox for workpackage 4 (Environmental models) uses the outputs from the dynamic models to matrices , which were developed using current guidelines for tilapia and shrimp as outlined by the GAA (2008a; 2008b). The matrix uses the maximum and minimum values for both modelled and measured data to provide an average score of 1-5 (poor- good) which can be applied to the groups identified in Chapter 4 as a reference if there is no data available to carry out modelling work (see Appendix 3).

## Conclusions

The models overall provide an indication of the effect of water management practices on the water quality, suggesting that the water source plays a primary role in the production system nutrient balance. This knowledge allows the farmer to address any water exchange practices and focus any water quality monitoring activities to the source water in addition to the pond water. This may allow the farmer to decide the best time to exchange water without introducing high levels of nutrients into the farm and possibly reducing the levels in the effluent released. It should not be seen as a way to increase inputs to the farm.

The models produced may be used as indicators of water quality, however would require further data in order to completely validate them. This would involve further negotiations with farmers in order to gain access in an industry that has received negative media attention in recent years. Thusly modelling should not be used as a replacement for real time data collection as assumptions are made based on the state of the system at a particular point in time and do not account for external factors placing pressure on the system. They do however provide an insight into the effect certain activities have on a particular parameter and can be used to estimate the sustainability of an aquaculture system through the use of indexes or guidelines.

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# APPENDIX

## 1. WATER MANAGEMENT FARMER SURVEY CONTRIBUTION,

## 2. POWERSIM STUDIO 8 MODELS (INITIAL MODEL POWERSIM DIAGRAM and equations),

## AND

## 3. RAPID ASSESSMENT TOOLBOX REPORT

## WORK PACKAGE 4: ENVIRONMENTAL MODELS

# APPENDIX 1

**Work Package 4 – Questionnaire**

**We have put questions in that are relevant to WP 4 and developing environmental models. We think there will be an overlap with other work packages. Ranked by importance (1) = the most important.**

**General Information (for deliverables 4.2, 4.3)**

(1)Name of farm: - ______________________________________________

(1)Brief description of location and surrounding land use: - ________________________

______________________________________________

______________

(1)GPS co-ordinates (in UTM reference system):- ______________________

(1)Photo number(s) (a – facing North) _____________________ (b – facing South) ____________________

- Wide angle photographs capturing as much of farm as possible

(1)Size of farm: - ______________________ha (2)Age of farm ____________ years

(1)Type of farm: - ☐ Cages ☐ Ponds ☐ Other - ______________________

(1)Size of cages or ponds: - _________________ $m^2$ (1) Number of cages or ponds: - __________

(1)Average depth of cage/pond: - ____________m

(3)Brief drawing of farm layout: -

N

(1)Species farmed : - _________________________________

(1)Stocking density : - _________________________________

(1)Weight of species at harvest : - _______________________

(1)Average number of mortalities per full stock cycle : - __________

(2)Months stocked / harvested (Species A, Species B etc, stocked: 1, harvested: 2): -

| Janua ry | Februa ry | Marc h | Apr il | Ma y | Jun e | Jul y | Augu st | Septemb er | Octob er | Novemb er | Decemb er |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |

**(1)Water Quality (for deliverables 4.2, 4.3)**

| **Source of water entering farm** | **Is water treated before entering farm (y or n)** | **Method of treatment** | **Where effluent is discharged to** | **Number of times effluent discharged per rainy season** | **Number of times effluent discharged per dry season** | **Is water treated before leaving farm (y or n)** | **Method of tre** |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

***(Closed Systems)***

(1)% water exchange : - ___________________ Frequency of water exchange : - ___________________

(1)% water drained at harvest : - ____________

(1)% sediment removal (if any): - __________________ Frequency of sediment removal : - __________

***(Open Systems)***

(1)Flow rate : - ____________________ $ms^{-1}$

***(All systems)***

**(1)Nutrients (for deliverables 4.2, 4.3)**

| Feed | Composition | Amount fed (kg) | Number of times fed per day | FCR | Nitrogen content (%) | Phosphorus content (%) |
|---|---|---|---|---|---|---|
| | | | | | | |
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| | | | | | | |

**(1)**

| Supplementary nutrients /Fertiliser | Composition | Amount applied (kg or Litres - please state) | Frequency of application | Nitrogen content (%) | Phosphorus content (%) |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
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**(1)Chemicals (for deliverables 4.2, 4.3)**

| | | Rainy Season | | | Dry Season | | |
|---|---|---|---|---|---|---|---|
| **Chemical name** | **Reason for use** | **Number of applications per month** | **Amount applied (kg or litres please state)** | **Higher (H) or Lower (L) than recommended dosage** | **Number of applications per month** | **Amount applied(kg or Litres please state)** | **Higher (H) or Lower (L) than recommended dosage** |
| | | | | | | | |
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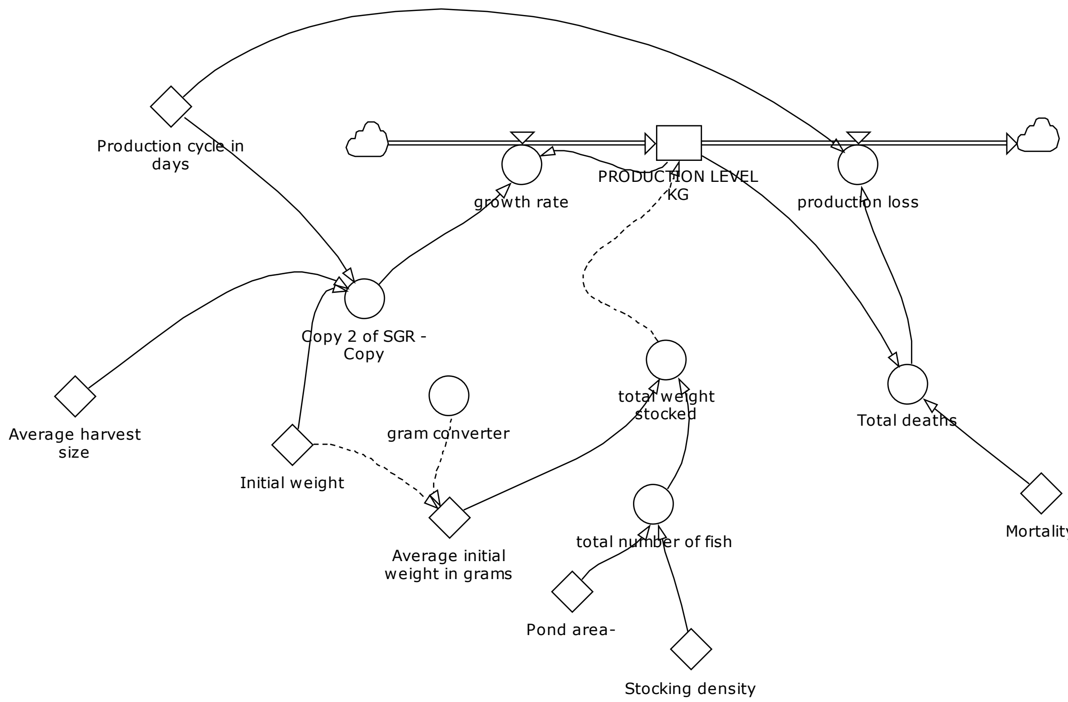
**(3)If it is possible to use a YSI meter (for deliverables 4.2, 4.3)**

| | Temperature | pH | DO (%) | DO (mg/l) | TDS (S/L) | EC (m3/cm) | ORP |
|---|---|---|---|---|---|---|---|
| Inflow | | | | | | | |
| Pond / Cage | | | | | | | |
| Outflow | | | | | | | |
| Other (please state) | Temperature | pH | DO (%) | DO (mg/l) | TDS (S/L) | EC (m3/cm) | ORP |
| a) | | | | | | | |
| b) | | | | | | | |
| C) | | | | | | | |

# APPENDIX 2

# POWERSIM SUBMODELS AND EQUATIONS

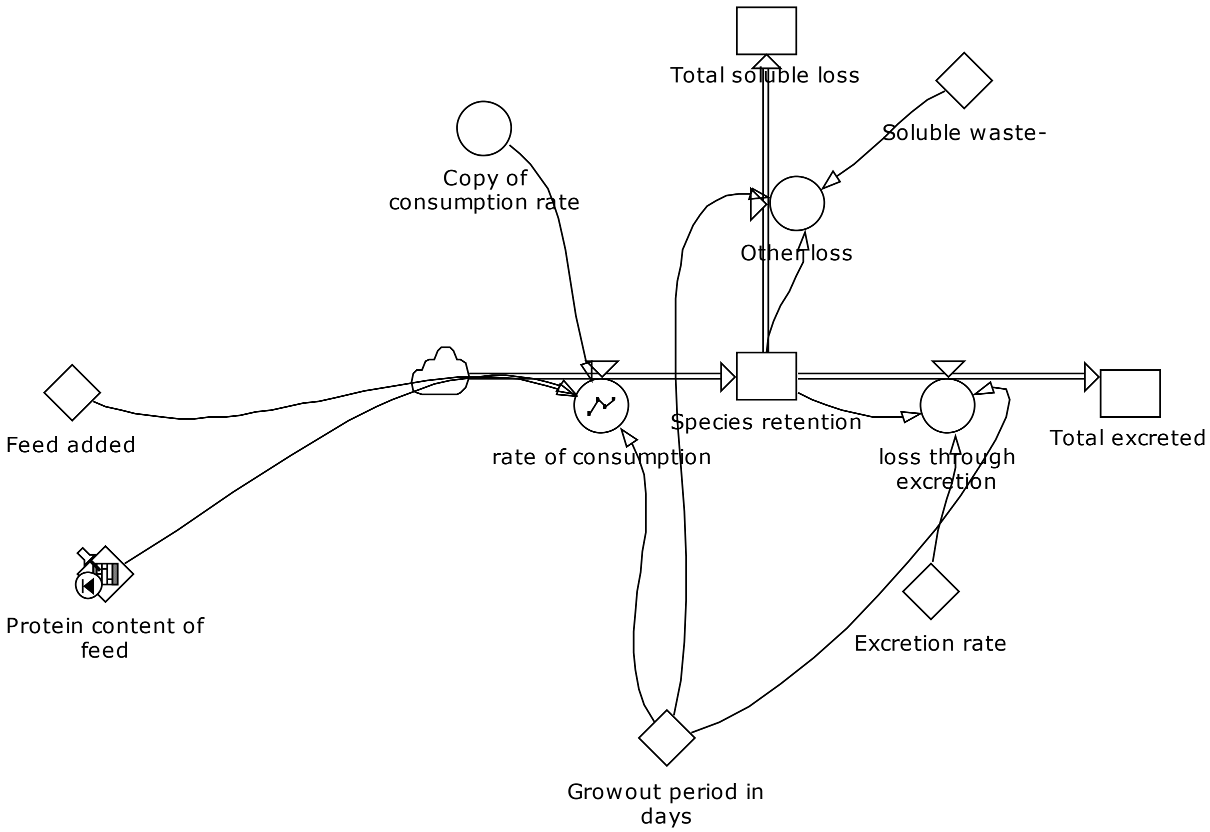
## 2.1 Production submodel



## 2.2 Production module equations (Using tilapia example data)

| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | Production level-KG | total weight stocked | kg |
| CONSTANT | Production cycle in days | 180 | da |
| | Average harvest size | 500 | g |
| | Initial weight | 30 | g |
| | Average initial weight in grams | 30 | g |
| | Pond area | 10000 | m2 |
| | Stocking denisity | 2 | individuals/m2 |
| | Mortality | 25 | % |
| AUXILLIARY | SGR | (LN('Average harvest size')-LN('Initial weight'))*100<<%>>/'Production cycle in days' | %/day |
| | Gram converter | 1 | g |
| | Total number of fish | Pond area'*'Stocking density' | individuals |
| | Total stoked weight | Average Initial weight in grams'*'Total number of fish' | kg |
| | Total deaths | ('Production levels-kg'*'Mortality') | kg |
| FLOW | Growth rate | Production levels-kg'*'SGR' | kg/da |
| | Production loss | Total death'/'Production cycle in days' | kg/da |

## 2.3 Species and feeding submodel



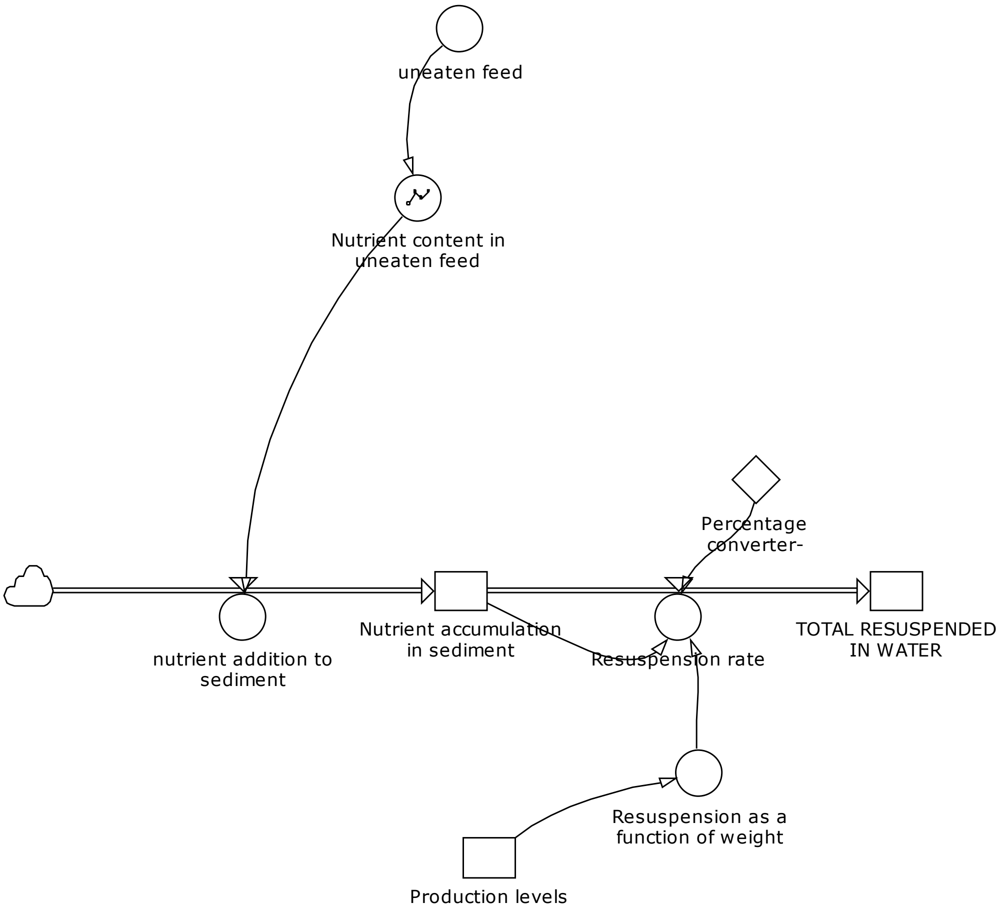
## 2.4 Species and feeding module equations (using tilapia example data for Nitrogen)

| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | Species retention | 0 | kg |
| | Total soluble loss | 0 | kg |
| | Total excreted | 0 | kg |
| CONSTANT | Feed added | 13002.96 | kg |
| | Protein content of feed | 32 | % |
| | Growout period in days | 180 | days |
| | Excretion rate | 90 | % |
| | Soluble waste | 5 | % |
| AUXILLIARY | consumption rate | 90 | % |
| FLOW | Rate of consumption | ((Feed added*('Protein content'/6.25))*'consumption rate')/growout period in days | kg/da |
| | loss through excretion | (Species retention*excretion rate)/growout period in days | kg/da |
| | other loss | (species retention*'soluble waste')/growout period in days | kg/da |

## 2.5 Species and feeding module equations (using tilapia example data for Phosphorus)

| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | Species retention | 0 | kg |
| | Total soluble loss | 0 | kg |
| | Total excreted | 0 | kg |
| CONSTANT | Feed added | 13002.96 | kg |
| | Phosphorus content of feed | 1.4 | % |
| | Growout period in days | 180 | days |
| | Excretion rate | 68 | % |
| | Soluble waste | 5 | % |
| AUXILLIARY | consumption rate | 90 | % |
| FLOW | Rate of consumption | ((Feed added*('Phosphorus content'))*'consumption rate')/growout period in days | kg/da |
| | loss through excretion | (Species retention*excretion rate)/growout period in days | kg/da |
| | other loss | (species retention*'soluble waste')/growout period in days | kg/da |

## 2.6 Sedimentation submodel



# 2.7 Sediment module equations (using tilapia example data for Nitrogen)

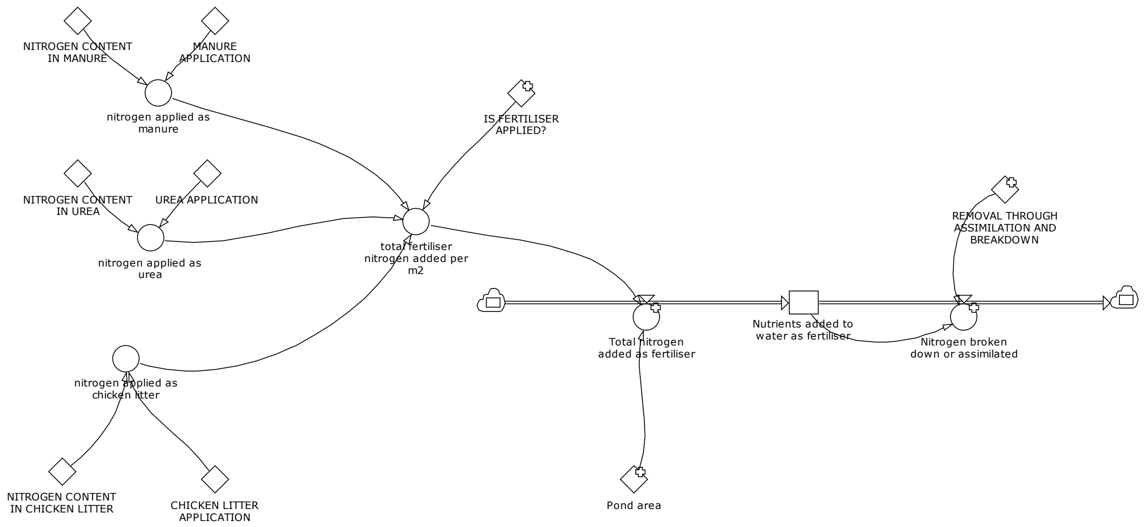
| **Object** | **Name** | **Input** | **Units** |
|---|---|---|---|
| LEVEL | Nutrient accumulation in sediment | 0 | kg |
| | Total resuspended in water | 0 | kg |
| | Production level- kg (production submodel) | Total weight stocked *(from production submodel)* | |
| CONSTANT | Percentage converter | 1 | % |
| AUXILLIARY | Uneaten feed | (100<<%>>-'consumption rate')*Feed added *(From species and feeding submodel)* | kg |
| | Nutrient content in uneaten feed | Uneaten feed'*('Protein content'/6.25) (*Protein content from species and feeding submodel*) | kg |
| | Resuspension as a function of weight | (85.1*'Production level- kg')/(49.7<<kg>>+'Production level- kg') | |
| FLOW | Nutrient addition to sediment | ('Nutrient content in uneaten feed'/'Production cycle in days')+loss through excretion *(Production cycle in days from production model; loss through excretion from species and feeding model)* | kg/day |
| | Resuspension rate | Nutrient accumulation in sediment'*(('Resuspension as a function of weight'*'Percentage converter')/growout period in days) *(growout period in days connected from species and feeding model)* | kg/day |

## 2.8 Sediment module equations (using tilapia example data for Phosphorus)

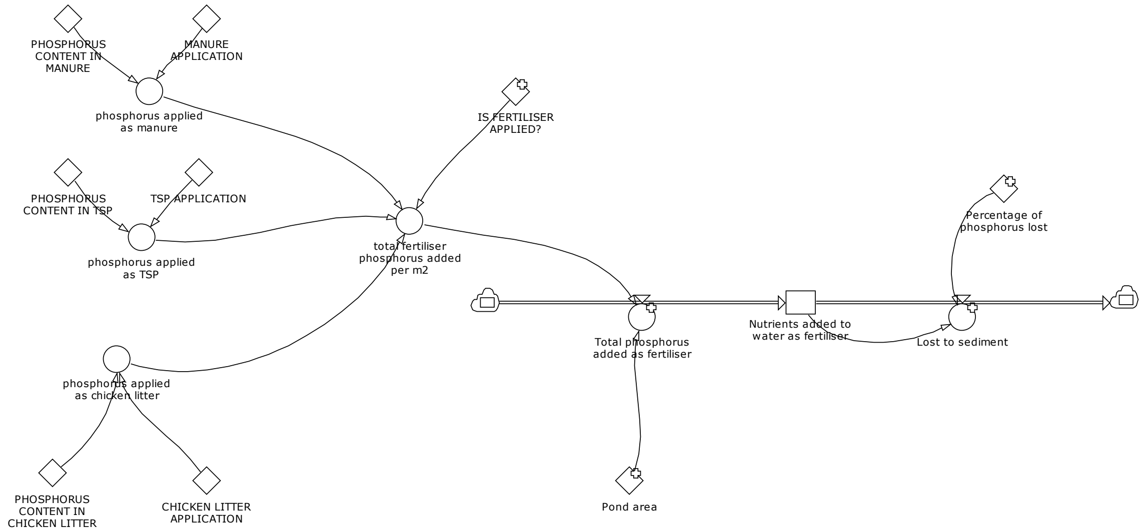
| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | Nutrient accumulation in sediment | 0 | kg |
| | Total resuspended in water | 0 | kg |
| | Production level- kg (production submodel) | Total weight stocked *(from production submodel)* | |
| CONSTANT | Settling rate | 20 | %/cycle |
| AUXILLIARY | Uneaten feed | (100<<%>>-'consumption rate')*Feed added *(From species and feeding submodel)* | kg |
| | Nutrient content in uneaten feed | Uneaten feed'*('Phosphorus content of feed) (*Protein content from species and feeding submodel*) | kg |
| FLOW | Nutrient addition to sediment | ('Nutrient content in uneaten feed'/'Production cycle in days')+Loss through excretion+ 'Phosphorus lost to sediment' *(Production cycle in days from production model; loss through excretion from species and feeding model)* | kg/day |
| | Resuspension rate | Settling rate'*'Nutrient accumulation in sediment' *(growout period in days connected from species and feeding model)* | kg/day |

# 2.9 Fertilisation submodel

## Nitrogen




## Phosphorus



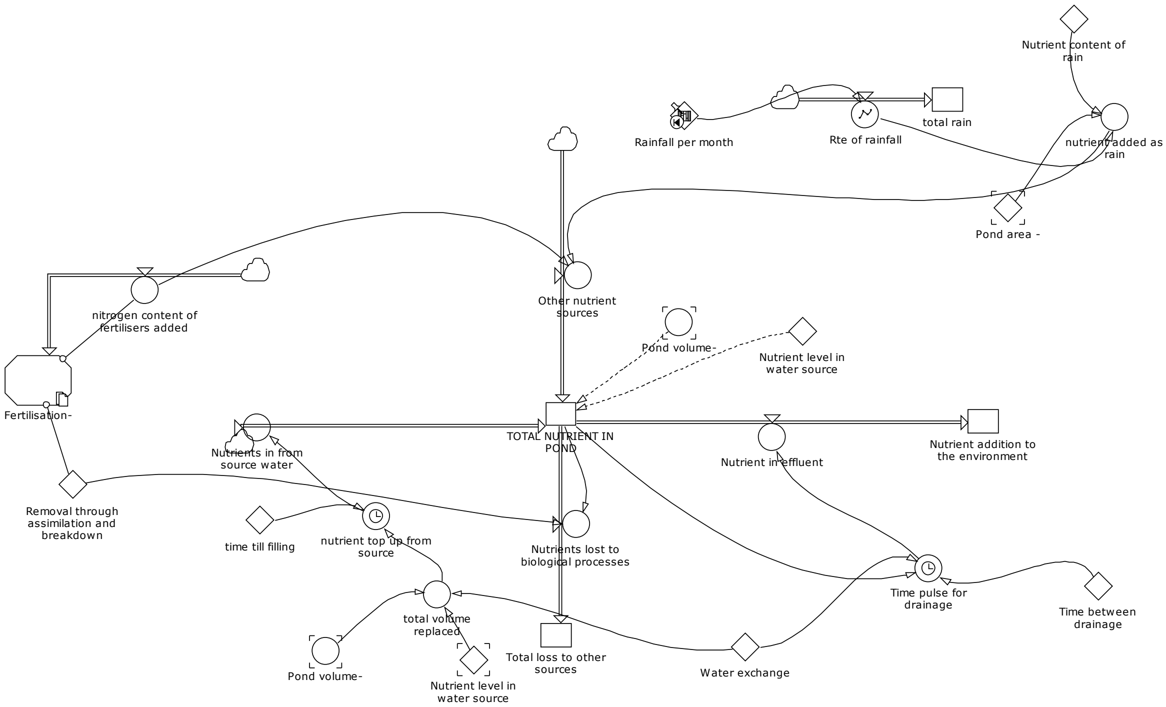
## 2.10 Fertilisation module equations (using tilapia example data for Nitrogen)

| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | Nutrients added to water as fertiliser | 0 | kg |
| CONSTANT | Nitrogen content in manure | 1.46 | % |
| | Manure application | 0.102 | kg/m2/week |
| | Nitrogen content in Urea | 46 | % |
| | Urea application | 0.00306 | kg/m2/week |
| | Nitrogen content in chicken litter | 2.75 | % |
| | Chicken litter application | 0.05 | kg/m2/week |
| | Pond area | 10000 *(from production model)* | m2 |
| | Removal through assimilation and breakdown | 17.4 | %/day |
| | Is fertiliser applied | True/False | NA |
| AUXILLIARY | Nitrogen applied as manure | 'Manure application'*'Nitrogen content in manure' | kg/m2/week |
| | Nitrogen applied as urea | Urea application'*'Nitrogen content in Urea' | kg/m2/week |
| | Nitrogen applied as chicken litter | Chicken litter application'*'Nitrogen content in chicken litter' | kg/m2/week |
| | Total fertiliser Nitrogen added per m2 | IF('Is fertiliser applied',('Nitrogen applied as chicken litter'+ 'Nitrogen applied as manure'+ 'Nitrogen applied as Urea'),0<<kg/m^2/wk>>) | kg/m2/week |
| FLOW | Total Nitrogen added as fertiliser | 'total fertiliser Nitrogen added per m2'*'Pond area' | kg/week |
| | Nitrogen Broken down or assimilated | Nitrogen Added As Fertiliser To Water'*'Removal through assimilation and breakdown' | kg/day |

## 2.11 Fertilisation module equations (using tilapia example data for Phosphorus)

| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | Nutrients added to water as fertiliser | 0 | kg |
| CONSTANT | Phosphorus content in manure | 0.55 | % |
| | Manure application | 0.102 | kg/m2/week |
| | Phosphorus content in TSP | 46 | % |
| | TSP application | 0.00306 | kg/m2/week |
| | Phosphorus content in chicken litter | 2.46 | % |
| | Chicken litter application | 0.05 | kg/m2/week |
| | Pond area | 10000 *(from production model)* | m2 |
| | Percentage of Phosphorus lost | 80 | %/day |
| | Is fertiliser applied | True/False | NA |
| AUXILLIARY | Phosphorus applied as manure | 'Manure application'*'Phosphorus content in manure' | kg/m2/week |
| | Phosphorus applied as urea | TSP application'*'Phosphorus content in TSP' | kg/m2/week |
| | Phosphorus applied as chicken litter | Chicken litter application'*'Phosphorus content in chicken litter' | kg/m2/week |
| | Total fertiliser phosphorus added per m2 | IF('Is fertiliser applied',('phosphorus applied as chicken litter'+ 'phosphorus applied as manure'+ 'phosphorus applied as TSP'),0<<kg/m^2/wk>>) | kg/m2/week |
| FLOW | Total phosphorus added as fertiliser | 'total fertiliser phosphorus added per m2'*'Pond area' | kg/week |
| | Lost to sediment | Phosphorus Added As Fertiliser To Water'*'Percentage of phosphorus lost' | kg/day |

# 2.13 Water Quality submodel



## 2.14 Water quality module equations (using tilapia example data for Nitrogen)

| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | Total rain | 0 | mm |
| | Total nutrients in pond | Nutrient level in water source'*'Pond volume' | kg |
| | Nutrient addition to the environment | 0 | kg |
| | Total loss to other sources | 0 | kg |
| CONSTANT | Rainfall per month | array of average rainfall data for each month | mm/month |
| | Nutrient content of rain | 0.286 | mg/l |
| | Pond area | 10000 *(Connected from production model)* | m2 |
| | Nutrient level in water source | 1.51 | mg/l |
| | Time till filling | 2 | days |
| | Water exchange | 15 | % |
| | Time between drainage | 1 | day |
| | Removal through assimilation and breakdown | 17.4 | %/day |
| AUXILLIARY | Pond volume | 10000 | m3 |
| | Total volume replaced | ('Pond volume'*Water Exchange)*'Nutrient level in water source' | mg |
| | Nutrients added as rain | ('Rate of rainfall'*'Pond area')*'Nutrient content of rain' | mg/month |
| | Time pulse for drainage | PULSE(Water Excange*'Total Nutrients in pond',STARTTIME+14<<da>>,'time between drainage') | kg/cycle |
| | nutrient top up from source | PULSE('total volume replaced',STARTTIME+14.5<<da>>,'time till filling') | mg/day |
| FLOW | Rate of rainfall | Rainfall per month | mm/month |
| | Nutrients in from source water | Nutrient top up from source | mg/day |

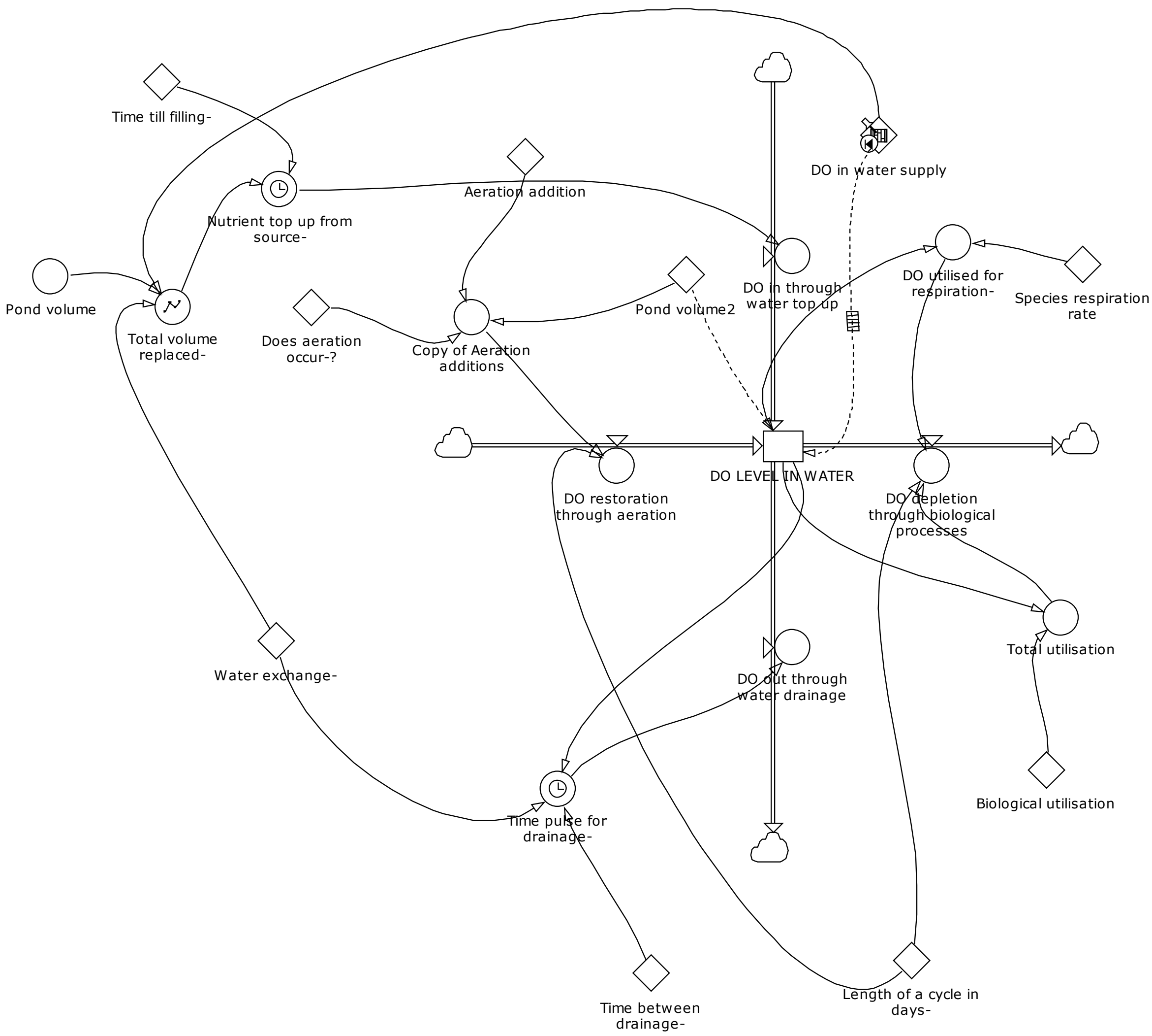
| | | | |
|---|---|---|---|
| | Nutrients lost to biological processes | Total Nutrients in pond'*fertilisation.'Removal through assimilation and breakdown' | kg/day |
| | Nutrients in effluent | Time pulse for drainage | kg/day |
| | Other nutrient sources | Nutrients added as rain'+Other loss+Resuspension rate+fertilisation.'nitrogen content of fertilisers added' *(Other loss from species and feeding model; resuspension rate from sedimentation model)* | mg/day |
| | Nitrogen content of fertilisers added | .'total fertiliser per m2'*.'Pond area' *(total fertiliser per m2 from fertiliser model; pond area from production model)* | kg/week |

## 2.15 Water quality module equations (using tilapia example data for Phosphorus)

| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | Total rain | 0 | mm |
| | Total nutrients in pond | Nutrient level in water source'*'Pond volume' | kg |
| | Nutrient addition to the environment | 0 | kg |
| | Total loss to other sources | 0 | kg |
| CONSTANT | Rainfall per month | array of average rainfall data for each month | mm/month |
| | Nutrient content of rain | 0.04 | mg/l |
| | Pond area | 10000 *(Connected from production model)* | m2 |
| | Nutrient level in water source | 0.56 | mg/l |
| | Time till filling | 2 | days |
| | Water exchange | 15 | % |
| | Time between drainage | 1 | day |
| | Lost to sediment | 80 | %/day |
| AUXILLIARY | Pond volume | 10000 | m3 |
| | Total volume replaced | ('Pond volume'*Water Exchange)*'Nutrient level in water source' | mg |
| | Nutrients added as rain | ('Rate of rainfall'*'Pond area')*'Nutrient content of rain' | mg/month |
| | Time pulse for drainage | PULSE(Water Excange*'Total Nutrients in pond',STARTTIME+14<<da>>,'time between drainage') | kg/cycle |
| | nutrient top up from source | PULSE('total volume replaced',STARTTIME+14.5<<da>>,'time till filling') | mg/day |
| FLOW | Rate of rainfall | Rainfall per month | mm/month |
| | Nutrients in from source water | Nutrient top up from source | mg/day |
| | Nutrients lost to biological processes | Total Nutrients in pond'*fertilisation.'Removal through assimilation and breakdown' | kg/day |

| | | | |
|---|---|---|---|
| | Nutrients in effluent | Time pulse for drainage | kg/day |
| | Other nutrient sources | Nutrients added as rain'+Other loss+Resuspension rate+fertilisation.'nitrogen content of fertilisers added' *(Other loss from species and feeding model; resuspension rate from sedimentation model)* | mg/day |
| | Nitrogen content of fertilisers added | .'total fertiliser per m2'*.'Pond area' *(total fertiliser per m2 from fertiliser model; pond area from production model)* | kg/week |

# 2.16 Dissolved Oxygen submodel



## 2.17 Dissolved Oxygen module equations

| Object | Name | Input | Units |
|---|---|---|---|
| LEVEL | DO level in water | DO in water supply*'Pond volume' | mg |
| CONSTANT | Time till filling | 1.2 | days |
| | Water exchange | 15 | % |
| | Time between drainage | 1 | days |
| | Length of a cycle in days | 180 | days |
| | Biological utilisation | 77.89 | % |
| | Species respiration rate | 22.5 | % |
| | DO in water supply | 4.12 | mg/l |
| | Pond volume 2 | 10000 | m3 |
| | Aeration addition | 4.7 | mg/l |
| | Does aeration ocur? | true/false | |
| AUXILLIARY | Pond volume | 10000 | m3 |
| | Total volume replaced | (' Pond volume'*'Water Exchange')*'DO in water supply' | mg |
| | Total utilisation | DO level in water'*'Biological utilisation' | mg |
| | DO utilised for respiration | 'DO lovel in water'*'species respiration rate' | mg |
| | Actual aeration additions | IF(' Does aeration occur?',('Aeration addition'*'Pond volume'),(0.5<<mg/l>>*'Pond volume')) | mg |
| | DO top up from source | PULSE(Total volume replaced,STARTTIME+14.5<<da>>,'time till filling') | mg/day |
| | Time pulse for drainage | PULSE('Water Exchange'*'DO lovel in water',STARTTIME+14<<da>>,'Time between drainage') | mg/cycle |
| FLOW | DO in through water top up | Nutrient top up from water source | mg/day |

| | | | |
|---|---|---|---|
| | DO restoration through aeration<br>DO out through water drainage<br>DO depletion through biological processes | 'Actual Aeration additions'/'Length of cycle in days'<br>Time pulse for drainage<br>('DO utilised for respiration'+'Total utilisation')/'Length of cycle in days' | mg/day<br>mg/day<br>mg/day |

Sustaining Ethical Aquaculture Trade

# APPENDIX 3

## Rapid Assessment Toolbox Report
## Work package 4: Environmental models

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# Work Package 4: Dynamic Environmental Models

**Background**

Environmental degradation is a growing concern for aquaculture practitioners globally and it is especially important to reduce the impacts of the practices if further expansion is sought (FAO, 2012). Much of the major aquaculture species in South East Asia are cultured in closed pond systems. This helps to reduce any uncontrolled impact on the species cultured and also has the potential to reduce the impact of the farm on the environment. However with increasingly intensive practices it is important that the nutrient levels in culture systems are monitored to prevent indiscriminate releases of nutrients to the surrounding environment (Lin and Yi, 2003). Therefore a means of determining the effect of varying water management practices on the nutrient content of the waters leaving the farms is a highly sought after tool. Dynamic models can provide an insight in to the effect of varying these practices before implementing any changes in the real life situation, which may result in the cost outweighing the benefits (Ford, 2010). The models developed for the SEAT project simulate nutrient dynamics in culture ponds for the duration of the system of interest. The major inputs for all models were considered to be feed and fertiliser additions with sedimentation and water exchange being the major losses from the culture system.

**Model Description**

The models developed for the Rapid Assessment Toolbox were developed in the modelling software Powersim Studio 8. The models are used to determine the levels of total nitrogen, total phosphorus and dissolved oxygen in the culture system.
The model combines environmental and biological components to provide a holistic overview of the outputs of practical culture systems. There are four main components to the construction of the model (fig 1):

- Production: determines the biomass produced from the culture period based on specific growth rates and mortalities of the species
- Organism: utilises a mass balance for the biological uptake and excretion of X based on feed application and content of X versus the physiological uptake of the compound in the given species
- Sediment: A simple sediment accumulation module accounting for food wastage and addition of faeces to the system.
- Water: The water component evaluates all the inputs of X to the water, taking into account fertilisation activities, water exchange and any biological breakdown of the substances.

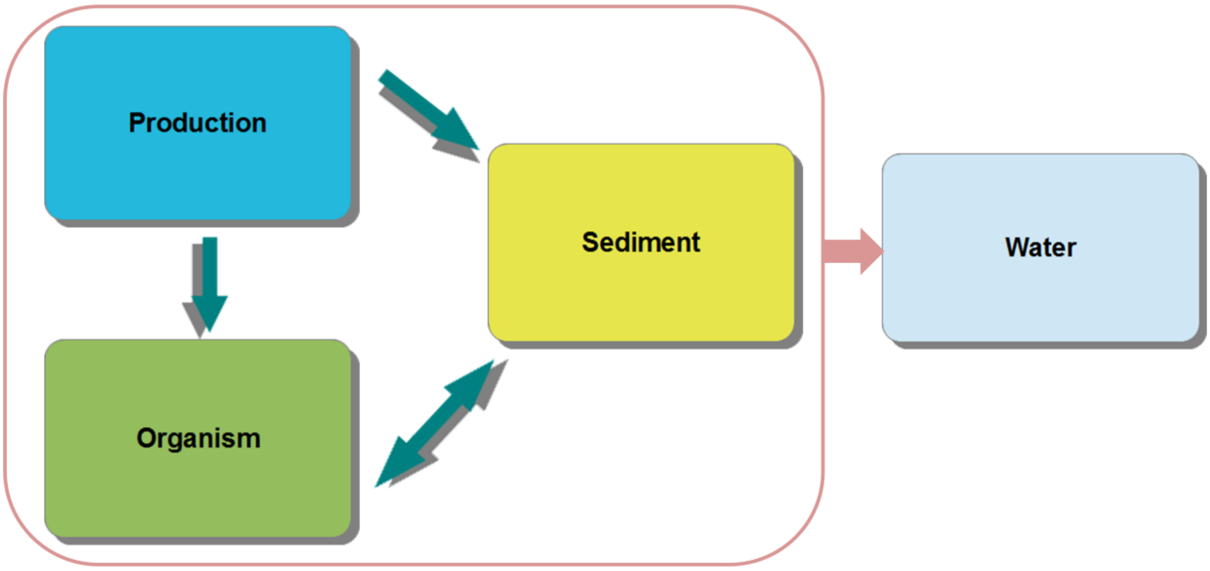



Figure 1: Outline of the model construction

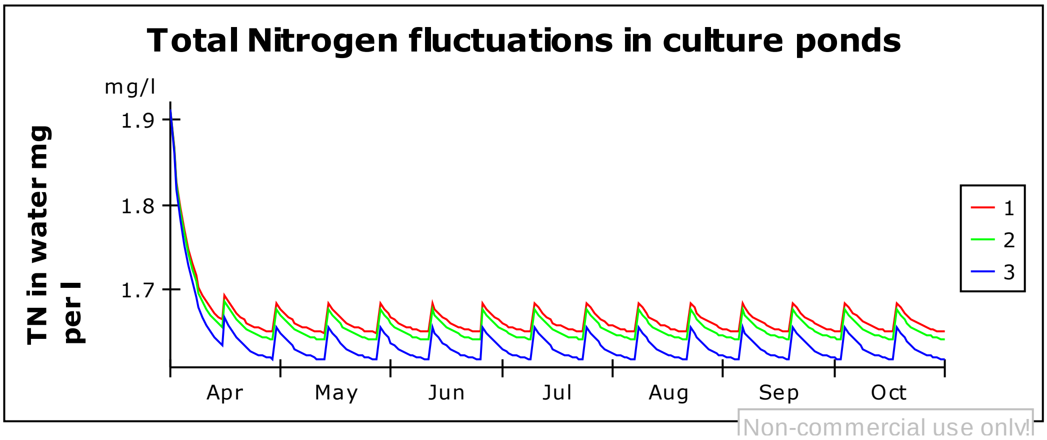
**Case study and application - Chinese Shrimp and pangasius in Vietnam**
Farms identified for study by the SEAT project were grouped objectively in a cluster analysis using information collected regarding water management practices. From the analysis output, 4 groupings were identified for Chinese shrimp and 3 groupings for Vietnamese pangasius, shown in tables 1 and 2. The models were then tailored to a farm from each of the groupings using both database information and measured data collected from the specified farm. The model outputs show the pattern of accumulation and deletion of the nutrients throughout the cycle of production relative to the management practices (fig 2 & 3).

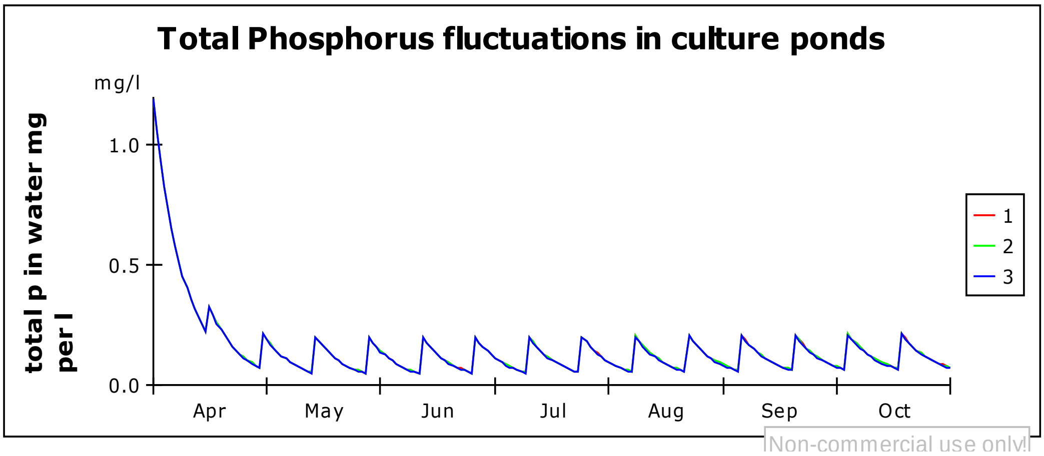
Table 1. Description of groupings identified for shrimp from multivariate analysis

| Group number | Brief Description |
|---|---|
| 1 | Water sourced from mangroves or sea, uses storage ponds |
| 2 | Monthly water exchange approximately, water is treated chemically |
| 3 | Farms sometimes utilise 2nd source of water, no storage ponds used |
| 4 | Most water sourced from ground water |

Table 2. Description of groupings for pangasius identified through multivariate analysis

| Group number | Brief Description |
|---|---|
| 1 | No use of fertilisers, storage ponds or aeration. Water exchange varies widely |
| 2 | 30% or more water exchange daily, fertilisers are used |
| 3 | Less than 30% water exchange daily, storage ponds are used |



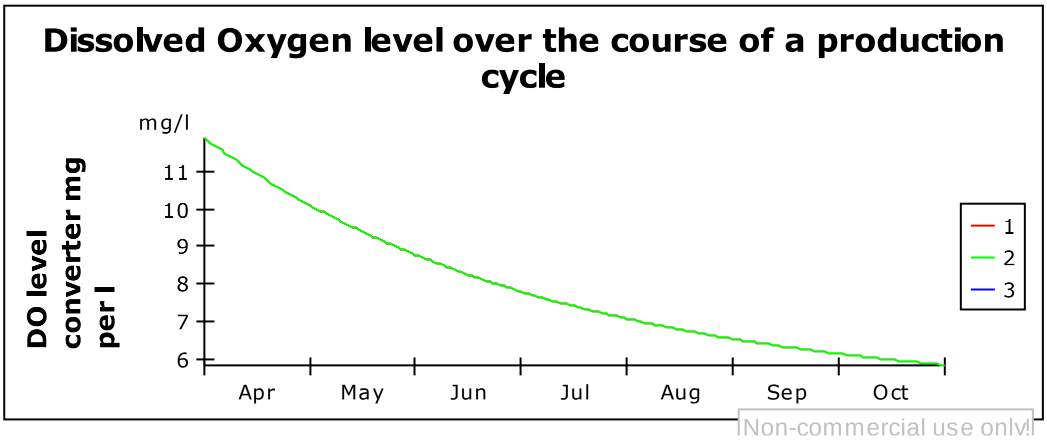
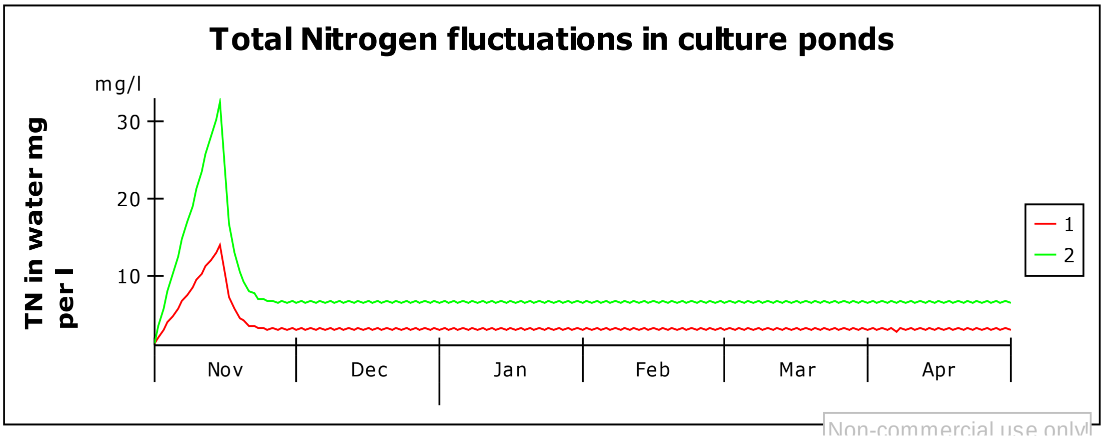
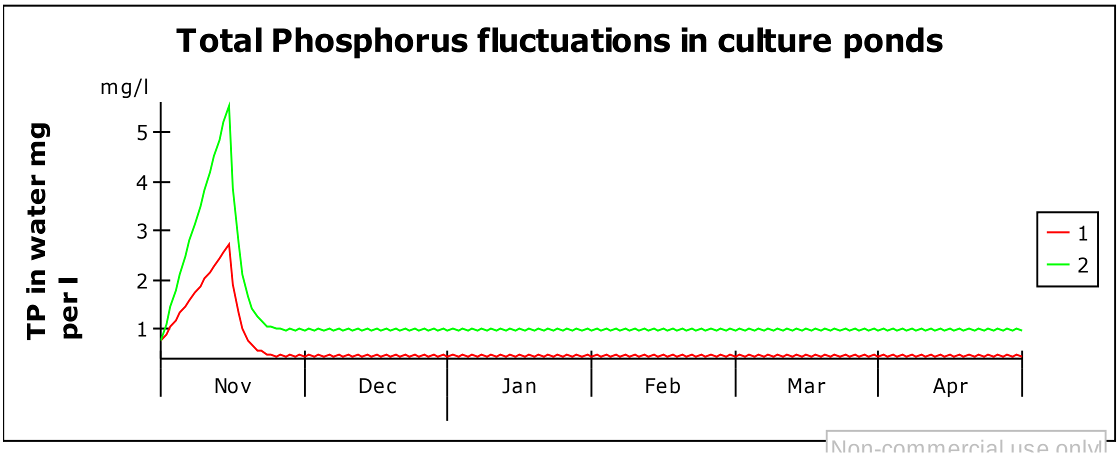




Figure 2. Example of outputs from a shrimp farm identified in China for Total nitrogen, total phosphorus and dissolved oxygen



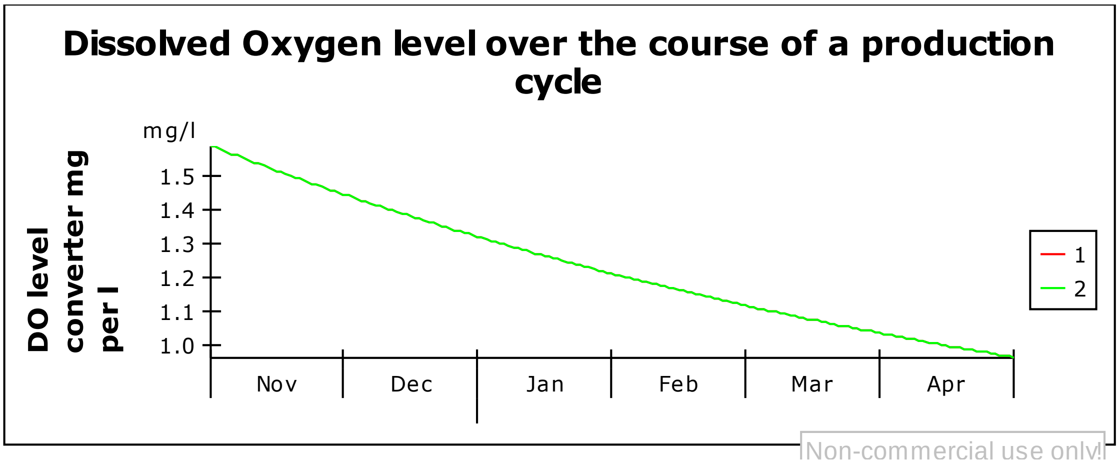




Figure 3. Example of outputs from a shrimp farm identified in China for Total nitrogen, total phosphorus and dissolved oxygen

**Application of the models towards environmental management**

Model such as the ones outlined above can be used to assist in environmental management and regulation. Although the outputs are tailored to a specific farm, each of the farms represents a group in which a range of farms will be categorised. These farms can then be associated with the outputs from the case study farms by assigning a score to the group as a whole. For the SEAT project Matrices were produced using the outputs from the case study farms and scoring the maximum and minimum values for both modelled and measured data (fig 4 & 5). This was then averaged to produce an overall score for each group, which can be used as a reference point when data is unavailable to carry out modelling activities. It should be noted that the BAP standards were used as a proxy for the scoring values, however further studies may indicate the need to increase or reduce these values depending on the species.

EAFI MATRIX CHINESE SHRIMP

| | TN | | Farm rank | |
|---|---|---|---|---|
| | Modelled | Measured | Modelled | Measured |
| Group1 | 1.912 | 6.527 | 5 | 1 |
| Group 2 | 4.449 | 6.659 | 2 | 1 |
| Group 3 | 5.236 | 4.642 | 1 | 2 |
| Group 4 | 4.19 | 5.185 | 2 | 1 |

| | TP | | Farm rank | |
|---|---|---|---|---|
| | Modelled | Measured | Modelled | Measured |
| Group1 | 1.192 | 0.463 | 1 | 2 |
| Group 2 | 4.143 | 1.074 | 1 | 1 |
| Group 3 | 0.2545 | 0.873 | 4 | 1 |
| Group 4 | 0.965 | 1.604 | 1 | 1 |

| | DO | | Farm rank | |
|---|---|---|---|---|
| | Modelled | Measured | Modelled | Measured |
| Group1 | 5.837760269 | 4 | 3 | 1 |
| Group 2 | 6.940319538 | 5.2 | 4 | 3 |
| Group 3 | 5.891453138 | 4.8 | 3 | 2 |
| Group 4 | 6.903554793 | 5.23 | 4 | 3 |

EAFI MATRIX CHINESE SHRIMP

| | TN | | Farm rank | |
|---|---|---|---|---|
| | Modelled | Measured | Modelled | Measured |
| Group1 | 1.618672275 | 1.115 | 5 | 5 |
| Group 2 | 2.992784481 | 0.875 | 3 | 5 |
| Group 3 | 3.028281514 | 1.647 | 3 | 5 |
| Group 4 | 2.065316522 | 0.791 | 4 | 5 |

| | TP | | Farm rank | |
|---|---|---|---|---|
| | Modelled | Measured | Modelled | Measured |
| Group1 | 0.072232021 | 0.123 | 5 | 5 |
| Group 2 | 3.113685798 | 0.108 | 3 | 5 |
| Group 3 | 0.140897405 | 0.035 | 5 | 5 |
| Group 4 | 0.092523032 | 0.209 | 5 | 5 |

| | DO | | Farm rank | |
|---|---|---|---|---|
| | Modelled | Measured | Modelled | Measured |
| Group1 | 5.837760269 | 4 | 1 | 2 |
| Group 2 | 6.940319538 | 5.2 | 1 | 1 |
| Group 3 | 5.891453138 | 4.8 | 1 | 2 |
| Group 4 | 6.903554793 | 5.23 | 1 | 1 |

EAFI Matrix (CHINA)

| Rank | TN (mg/l) | TP(mg/l) | DO (mg/l) |
|---|---|---|---|
| 5 | 1 | 0.1 | 8 |
| 4 | 2 | 0.2 | 7 |
| 3 | 3 | 0.3 | 6 |
| 2 | 4 | 0.4 | 5 |
| 1 | 5 | 0.5 | 4 |

| | Modelled | | Measured | | | Average Rank |
|---|---|---|---|---|---|---|
| | TN | | | | | |
| | Max | Min | Modelled | | | |
| Group1 | 5 | 5 | 1 | 5 | 5 | 3 |
| Group 2 | 2 | 3 | 1 | 5 | 2.5 | 3 |
| Group 3 | 1 | 3 | 2 | 5 | 2 | 3.5 |
| Group 4 | 2 | 4 | 1 | 5 | 3 | 3 |

| | TP | | Farm rank | | | |
|---|---|---|---|---|---|---|
| | Max | Min | Modelled | | | |
| Group1 | 1 | 5 | 2 | 5 | 3 | 3.5 |
| Group 2 | 1 | 3 | 1 | 5 | 2 | 3 |
| Group 3 | 4 | 5 | 1 | 5 | 4.5 | 3 |
| Group 4 | 1 | 5 | 1 | 5 | 3 | 3 |

| | DO | | Farm rank | | | |
|---|---|---|---|---|---|---|
| | Max | Min | Modelled | | | |
| Group1 | 3 | 1 | 1 | 2 | 2 | 1.5 |
| Group 2 | 4 | 1 | 3 | 1 | 2.5 | 2 |
| Group 3 | 3 | 1 | 2 | 2 | 2 | 2 |
| Group 4 | 4 | 1 | 3 | 1 | 2.5 | 2 |

Figure 4. Matrix produced for Chinese Shrimp

EAFI matrix for Vietnamese pangasius

| | TN | | | Farm rank | |
|---|---|---|---|---|---|
| | Modelled | Measured | | Modelled | Measured |
| Group1 | 1.486691 | 18.329 | | 5 | 1 |
| Group 2 | 6.032082 | 5.768 | | 1 | 1 |
| Group 3 | 9.704024 | 6.274 | | 1 | 1 |

| | TP | | | Farm rank | |
|---|---|---|---|---|---|
| | Modelled | Measured | | Modelled | Measured |
| Group1 | 41244 | 9.534 | | 1 | 1 |
| Group 2 | 0.911681 | 1.811 | | 1 | 1 |
| Group 3 | 0.835 | 3.265 | | 1 | 1 |

| | DO | | | Farm rank | |
|---|---|---|---|---|---|
| | Modelled | Measured | | Modelled | Measured |
| Group1 | 2.47 | 1.5 | | 1 | 1 |
| Group 2 | 0.961813 | 2.1 | | 1 | 1 |
| Group 3 | 1.792684 | 2.9 | | 1 | 1 |

| | TN | | | Farm rank | |
|---|---|---|---|---|---|
| | Modelled | Measured | | Modelled | Measured |
| Group1 | 0.358 | 4.566 | | 5 | 2 |
| Group 2 | 1.187 | 2.544 | | 5 | 4 |
| Group 3 | 1.588084 | 3.671 | | 5 | 3 |

| | TP | | | Farm rank | |
|---|---|---|---|---|---|
| | Modelled | Measured | | Modelled | Measured |
| Group1 | 0.358 | 0.639 | | 5 | 5 |
| Group 2 | 0.36982 | 0.35 | | 5 | 5 |
| Group 3 | 0.217567 | 0.499 | | 5 | 5 |

| | DO | | | Farm rank | |
|---|---|---|---|---|---|
| | Modelled | Measured | | Modelled | Measured |
| Group1 | 2.47 | 1.5 | | 4 | 5 |
| Group 2 | 0.961813 | 2.1 | | 5 | 4 |
| Group 3 | 1.792684 | 2.9 | | 5 | 4 |

| EAFI Matrix | | | |
|---|---|---|---|
| Rank | TN (mg/l) | TP(mg/l) | DO (mg/l) |
| 5 | 1 | 0.1 | 8 |
| 4 | 2 | 0.2 | 7 |
| 3 | 3 | 0.3 | 6 |
| 2 | 4 | 0.4 | 5 |
| 1 | 5 | 0.5 | 4 |

| | Modelled | | Measured | | | | Average Rank |
|---|---|---|---|---|---|---|---|
| | TN | | | | | | |
| | Max | Min | Modelled | | | | |
| Group1 | 5 | 5 | 1 | 2 | | 5 | 1.5 |
| Group 2 | 1 | 5 | 1 | 4 | | 3 | 2.5 |
| Group 3 | 1 | 5 | 1 | 3 | | 3 | 2 |

| | TP | | | Farm rank | | | |
|---|---|---|---|---|---|---|---|
| | Max | Min | | Modelled | | | |
| Group1 | 1 | 5 | 1 | 5 | | 3 | 3 |
| Group 2 | 1 | 5 | 1 | 5 | | 3 | 3 |
| Group 3 | 1 | 5 | 1 | 5 | | 3 | 3 |

| | DO | | | Farm rank | | | |
|---|---|---|---|---|---|---|---|
| | Max | Min | | Modelled | | | |
| Group1 | 1 | 4 | 1 | 5 | | 2.5 | 3 |
| Group 2 | 1 | 5 | 1 | 4 | | 3 | 2.5 |
| Group 3 | 1 | 5 | 1 | 4 | | 3 | 2.5 |

Figure 5. Matrix produced for Vietnamese pangasius

# Work Package 4 : spatial models

Two model frameworks were developed to assess the spatial characteristics of large catchments: site suitability and the risk of non-point source pollution. Study areas were selected and defined within a geographical context using catchments to set boundaries.

## 1. Site suitability

### Background

Many of the negative environmental impacts associated with aquaculture are due to poor planning and inappropriate site selection (Kumar and Cripps, 2012). Decision makers need to know where the most suitable areas are for culture as this allows identification of optimal areas for development and assessment of the availability of areas for food production. However, across large areas it can be costly to perform detailed field assessments of multiple locations. GIS can be used to develop spatial models which indicate the availability and suitability of a catchment; allowing the selection of the most suitable areas for more specific evaluation and potential development.

### Model description

Often models are developed for one specific area or system and wider applicability to other areas is an afterthought. Therefore to enable the application of the same model to different locations and species a multi-stage framework was developed which can be adapted to new areas and scenarios. Fig. 1 shows the model structure, where the outcomes of four major submodels (Pond, Species, System and Access) are added together, along with a constraints layer, to produce the final output; the overall site suitability model. The tiered approach represents the decision making process when evaluating an area for an aquaculture pond; where is the best place for a pond? What species can be farmed where? Could a sustainable system be established with regard to water availability and how easily accessible is that farm from transport networks and urban centres?

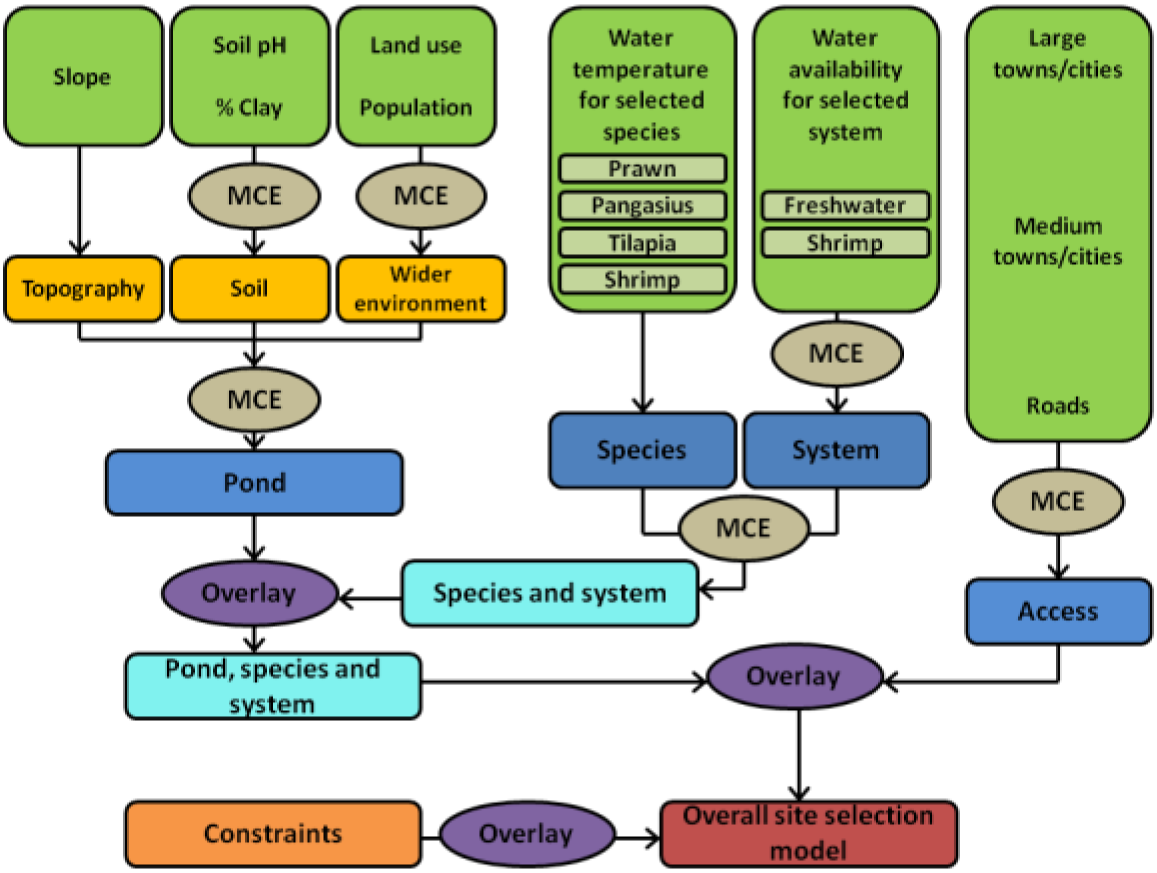



Fig. 1: Site suitability model structure

**Potential application**

The results of the overall site suitability models for shrimp in China and pangasius in Vietnam are shown in Fig. 2; as there are two outputs per species, the models can be used to evaluate seasonal differences in suitability and potential implications for production. This is highlighted in Figs. 2A and 2B which show a decrease in the availability of suitable areas for shrimp culture in China in the dry season compared to the rainy season; mainly due to low temperatures in the dry season, outwith the optimal range for culture. Figs. 2C and 2D only show a slight change in suitability within the study area in Vietnam, suggesting it would be suitable for year round production of pangasius in many areas. The models can also be used to evaluate areas which are not currently used for culture and decision makers can identify the most suitable locations where aquaculture could expand and develop. This allows detailed site specific assessment to be conducted at several pre-identified suitable sites rather than many random locations; saving time and money.

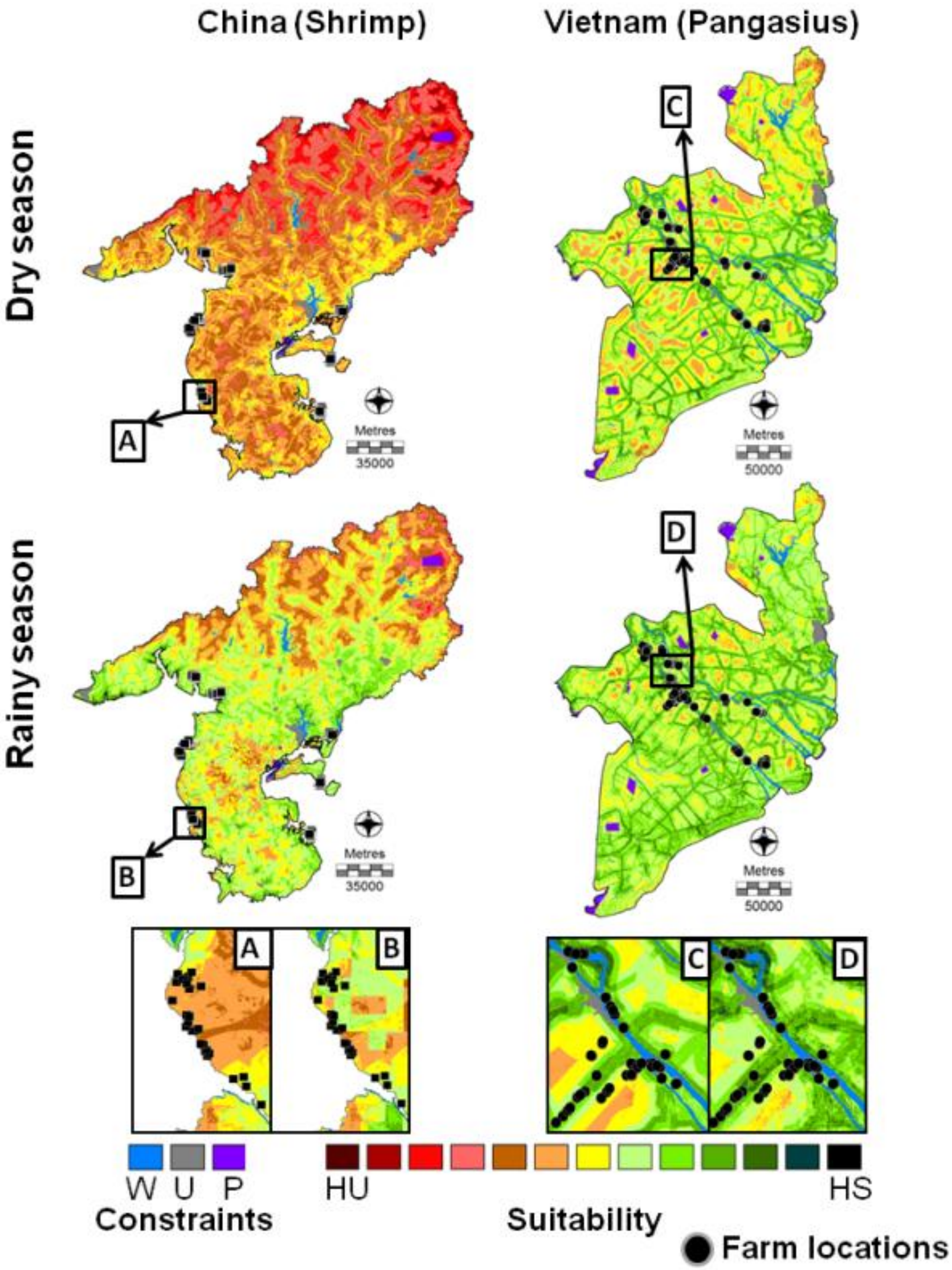



Fig. 2 : Overall site suitability models for shrimp in China and pangasius in Vietnam
W = Water, U = Urban, P = Protected areas
HU - Highly unsuitable, HS - Highly suitable

## 2. The risk of non-point source pollution

### Background

The accumulation of nutrients within aquatic systems can have serious detrimental impacts on water quality and aquaculture production. A significant source of nutrients in the wider environment is non-point source pollution (NPSP). NPSP is often spread across a large area and is generated from diffuse sources with no single point of entry (Frid and Dobson 2002; Cech, 2010) making it difficult to identify and monitor. Additionally, as NPSP is often intermittent and associated with seasonal land management practices and heavy rainfall (Carpenter et al., 1998) it can be difficult to measure. As part of work package 4, GIS-based models were developed which could be applied to large catchments; providing key stakeholders and decision makers extra information to assess the risk of NPSP and the identification of areas in need of further analysis or assistance.

### Model description

The models build upon work by previous studies (Munafò *et al*., 2005; Moltz *et al*., 2011; Zhang and Huang, 2011) and allow qualitative assessment of the risk of seasonal NPSP (nitrogen and phosphorus) within a study area. The overall framework is outlined in Fig. 3 and comprises of five indices; nutrient generation, runoff, transport, rainfall and population. These indices use data on land use, soil, rainfall, topography and hydrological conditions, and are weighted and then combined to produce the final outputs.

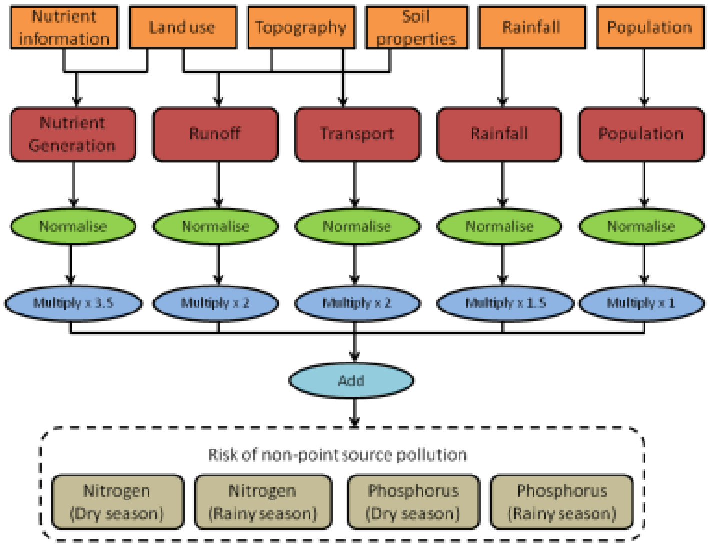



Fig 3: Non-point source pollution model structure

### Potential application

The models provide a visual estimate of risk which would be difficult to achieve outside of a spatial environment. However, it must be noted that the models are normalized on an individual basis and therefore one season should not be compared to another and *vice versa*. The models indicate the areas at risk of NPSP *within* the selected study area and season, allowing users to identify areas which may need further investigation. Fig. 4 shows the output of the nitrogen model for the study area in China during the dry season. The models can be used to identify areas at more risk (Fig. 4A) than others (Fig. 4B) this can then be used to prioritise monitoring in such areas, identify locations in need of site specific analysis or establish mitigation procedures. Monitoring, analysis and mitigation can be expensive and time consuming, therefore, this modelling approach allows a more effective strategy to assess and monitor NPSP as the areas most in need can be targeted first.

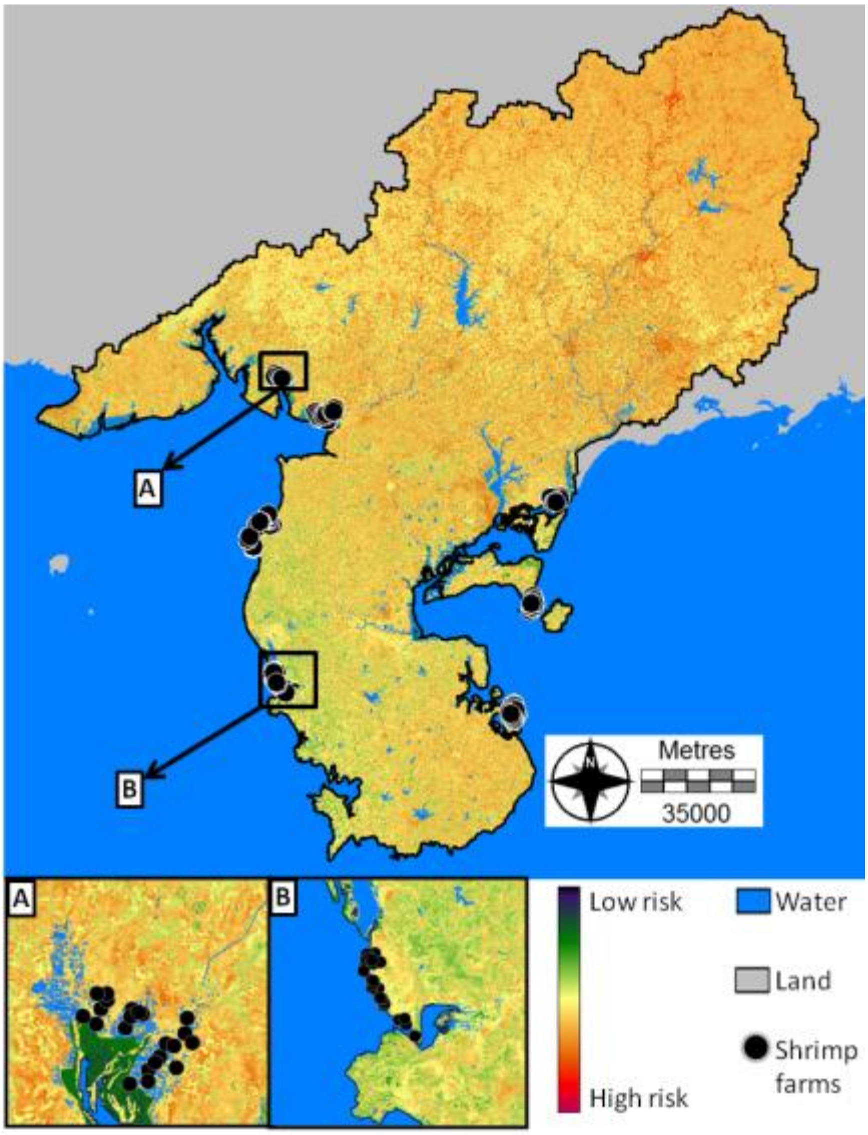



Fig 4: Risk of nitrogen NPSP in the dry season for the study area in China

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